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DEFINITION AND REDUCTION OF THE F-18 WINDSHIELD BIRDSTRIKE HAZARD

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This technical report has been reviewed and is approved for publication.

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Since 1983 there have been nine reported bird impacts on the F-18 windshield, resulting in one penetration and one injured pilot. The number of penetrations can be expected to increase as the F-18 fleet size increases. This program was initiated to develop a windshield system with an increased bird impact capability for the F-18 aircraft. The results of this seven-part study were integrated into a design recommendation.

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FOREWORD

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The work described herein was conducted during the period February 1986 to July 1988. Project supervision and technical assistance was provided through the Aerospace Mechanics Division of the University of Dayton Research Institute, with Dale H. Whitford, Supervisor, and Blaine S. West, Head, Applied Mechanics Group. The principal investigator was Gregory J. Stenger. Major contributions to this effort were made by Daniel R. Bowman and R. David Kemp.

The active support of Mr. Terry on this project is gratefully acknowledged. His comments, insights, and technical direction were most helpful. A special thanks to Messrs. Rich Gilpin and Jeff Newsome for providing the necessary information which made this study possible.

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INTRODUCTION

Since 1983 there have been nine reported bird impacts on the F-18 windshield, see Figure 1, resulting in one penetration. Associated with this penetration was an injury to the pilot. The number of penetrations can be expected to increase as the F-18 fleet size increases. There are approximately 270 aircraft in the fleet (mid-1986), with 84 aircraft being added per year to achieve a total fleet size of 1300 aircraft.

The Improved Windshield Protection Program Office (AFWAL/FDER) of the Air Force Wright Aeronautical Laboratory was contacted by NAVAIR to evaluate the F-18 windshield system and recommended an improved system having a birdstrike resistance capability consistent with the current and expected future mission requirements. FDER contracted with the University of Dayton Research Institute (UDRI) to conduct a seven-part study to develop and evaluate alternate transparency system concepts and to recommend a system which will provide the most cost effective approach meeting the design requirements and goals. The seven tasks which were considered in this transparency development/evaluation program are outlined in Figure 2 and listed below.

- o Define the requirements/goals, guidelines, criteria, and constraints
- o Identify alternate transparency systems
- o Conduct a parametric analysis of the alternate systems
- o Define the baseline bird impact capability
- o Evaluate manufacturing, optics, cost, maintenance, life cycle cost

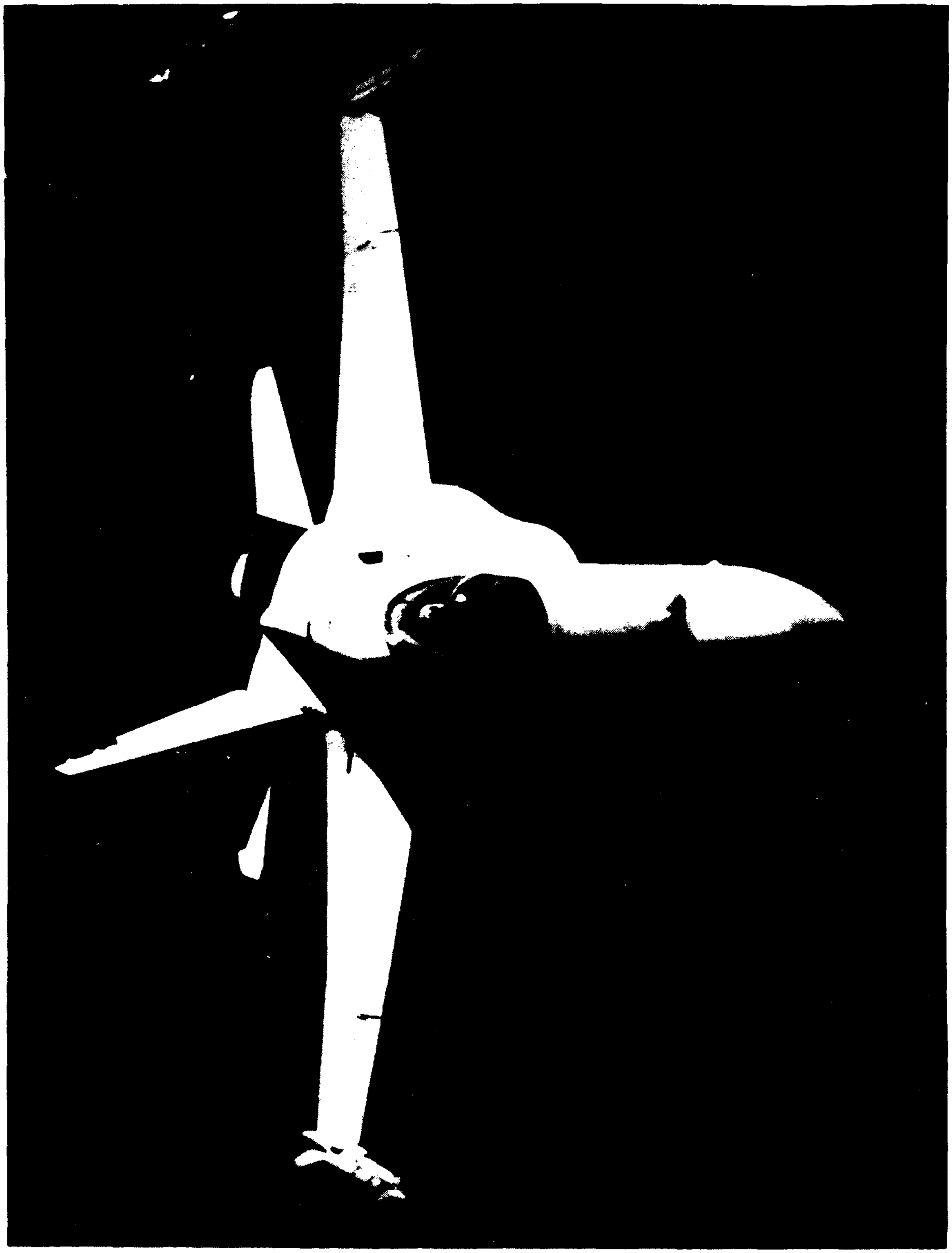


Figure 1. F-18 Aircraft.

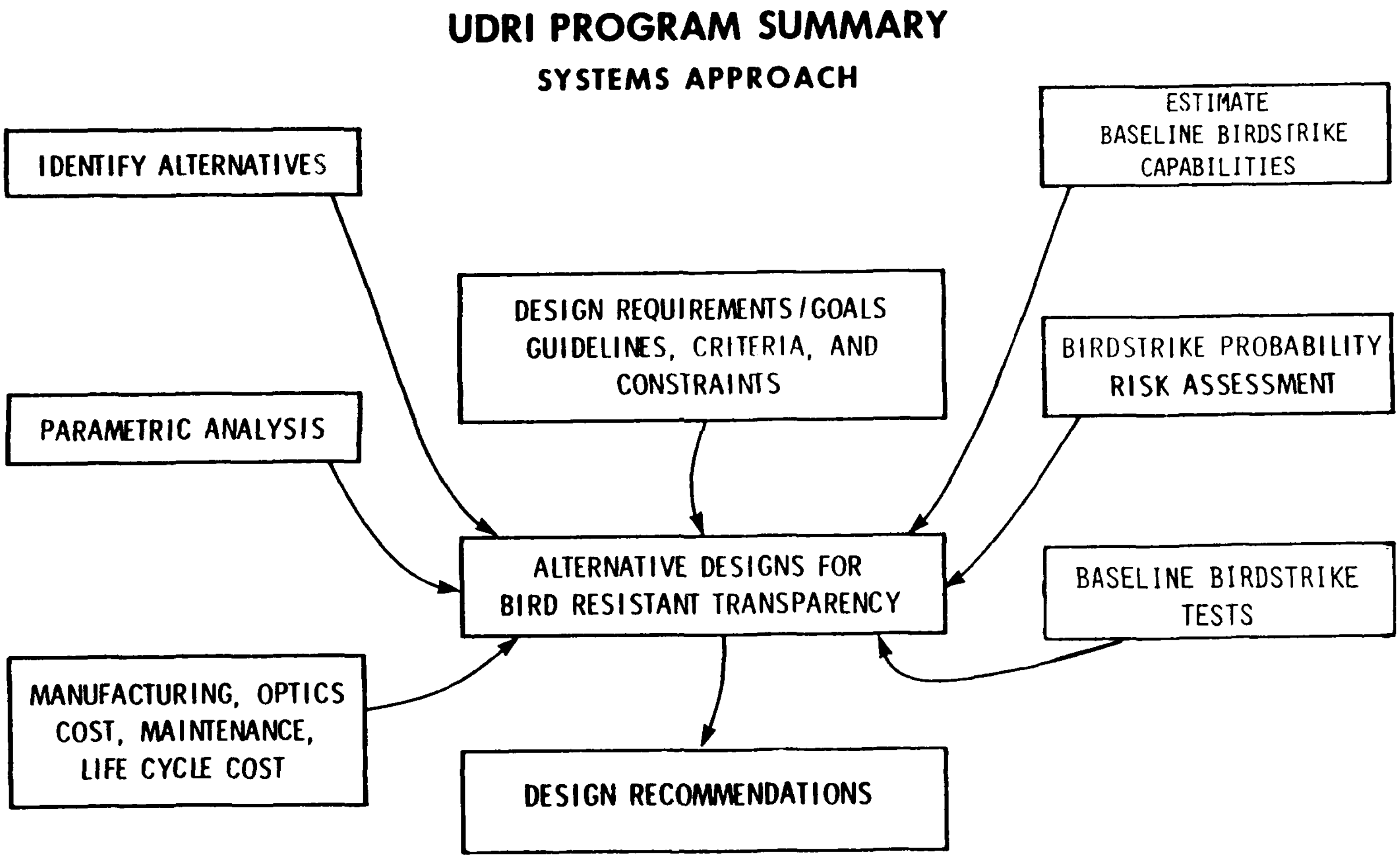


Figure 2. Tasks Considered in the F-18 Improved Transparencies Program.

- o Conduct a birdstrike probability risk assessment on the alternate systems
- o Conduct baseline bird impact tests

The following paragraphs discuss the results of each of these tasks and integrates the findings into the design recommendations.

The primary purpose of this study was to evaluate transparency systems with increased bird impact resistance capability. Because of the limited frontal area of the canopy, the threat of bird impacts on the canopy was not considered critical to aircraft survivability. As a result, this effort was limited to evaluating windshield systems; the canopy was not considered for redesign.

SECTION 2
DESIGN GUIDELINES, REQUIREMENTS AND CONSTRAINTS

The UDRI, in conjunction with the AFWAL Project Engineer, defined the guidelines and constraints that governed the design of the alternate windshield systems, as well as the evaluation of each of the design concepts. Similar programs have been conducted on the T-38, F-4, and A-7 aircraft, and the experience and knowledge gained in these programs were used to make critical decisions relating to optics, fabrication, maintainability, and life cycle costs. The design guidelines used to conduct the feasibility study are listed below.

(a) Maintain nominal 5-year windshield life.

(b) No decrease in maintainability with respect to existing transparencies is to occur.

(c) Maintain interchangeability with existing transparencies.

(d) Provide simplification of fleet retrofit.

(e) The capability to withstand hot gases from aircraft cannon is to be equivalent with current transparency.

The governing constraints were subdivided into requirements and goals. The requirements are those which must be totally satisfied and include:

o Birdstrike protection must be consistent with current and expected future mission requirements.

o The system must be producible using existing technology.

o Maintenance of alternate systems must be consistent with current practices.

- o Optics must meet current and expected future mission requirements including compatibility with night vision and HUD requirements.

The selected design must satisfy the above requirements and will consist of compromises between, and the optimization of, remaining design goals according to their relative importance. These other design goals are in the form of performance in certain key areas, namely:

- o Minimize weight
- o Minimize possibility of catastrophic failure resulting from birdstrikes above threshold capability
- o Minimize cost of ownership
- o Minimize technical risk
- o Maximize visibility
- o Maximize durability
- o Maximize thermal integrity
- o Minimize changes to exterior moldline, fairings, and associated hardware
- o Minimize spall during bird impact event.

SECTION 3
ESTIMATED BASELINE BIRDSTRIKE CAPABILITY

The F-18 windshield system consists of a 0.6-inch-thick monolithic stretched acrylic panel mounted to an assembled aluminum frame, fastened to the aircraft at six locations (see Figure 3), and is hinged at the forward edge. Baseline birdstrike test results were not available during the initial phase of this program, so the baseline birdstrike capability was estimated from parametric equations and test results on similar systems. These estimated capabilities were experimentally verified later in the program. Bird impacts above threshold capability may result in loss of pilot and/or aircraft.

The estimated current F-18 birdstrike resistance capability is summarized in Figure 4. The critical impact location is just forward of the aft arch along the aircraft centerline. The capability at this location was estimated to be 265 knots with a 4-pound bird (all capabilities are quoted for using a 4-pound bird). The transparency impact capability is generally lower near the support structure because of stress concentration at the interface. The 265-knot capability also represents the estimated capability of the aluminum aft windshield arch. The capability just aft of the forward arch is estimated to be 300 knots, increasing to 340 knots for a center-center impact. The capability increases outboard from centerline toward the sill because of the decreased bird impact angle.

The estimated capabilities for the stretched acrylic transparency were based on test data for similar systems and parametric equations, see Figure 5. Test results on the T-38 student windshield showed that the 0.6-inch-thick windshield has a capability of approximately 210 knots just forward of the aft arch, and 320 knots at the center-center impact point. It was

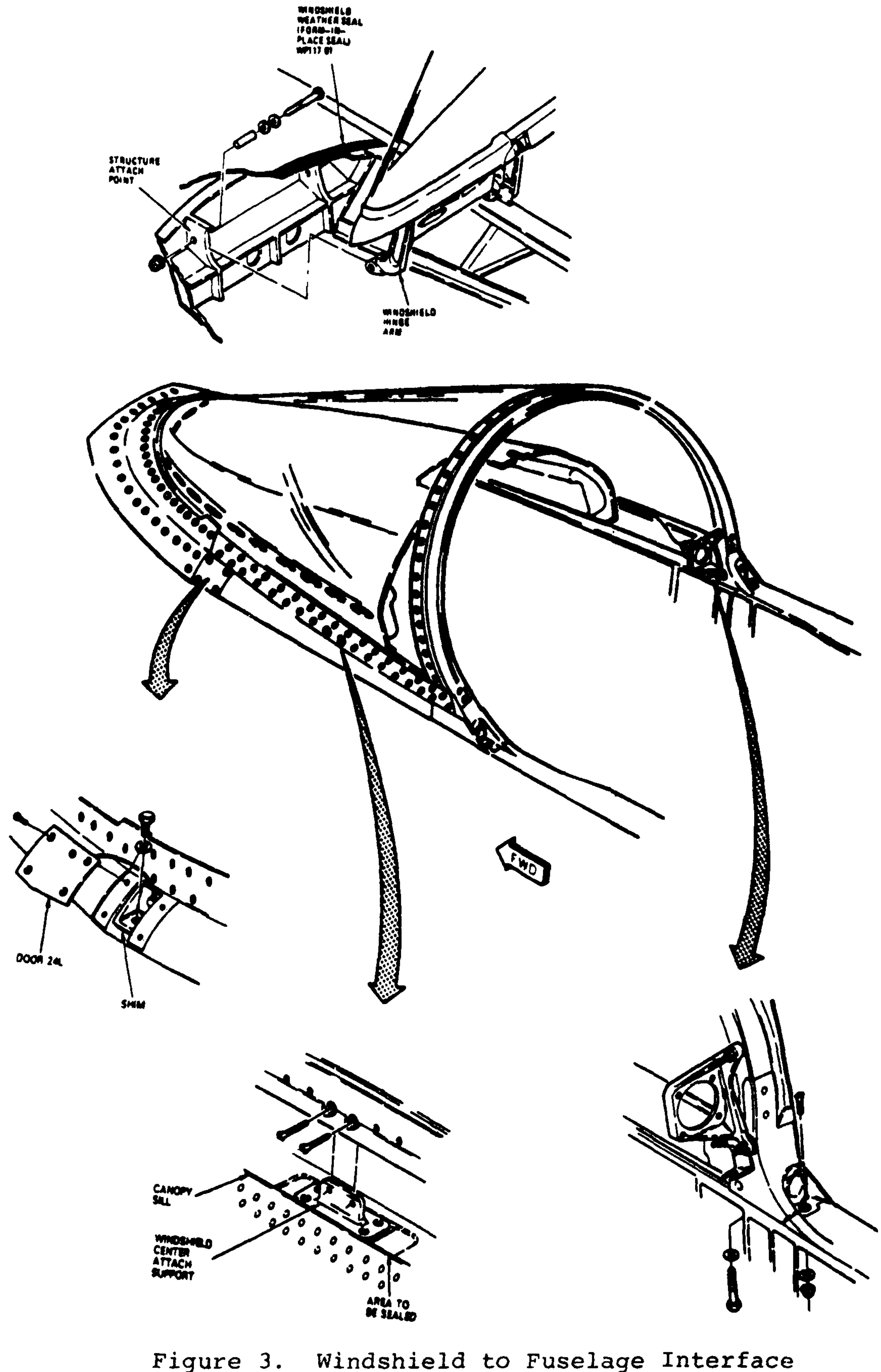


Figure 3. Windshield to Fuselage Interface
(Ref. T.O. A1-F18AC-120-300).

CURRENT F-18 WINDSHIELD CAPABILITY (ESTIMATED)

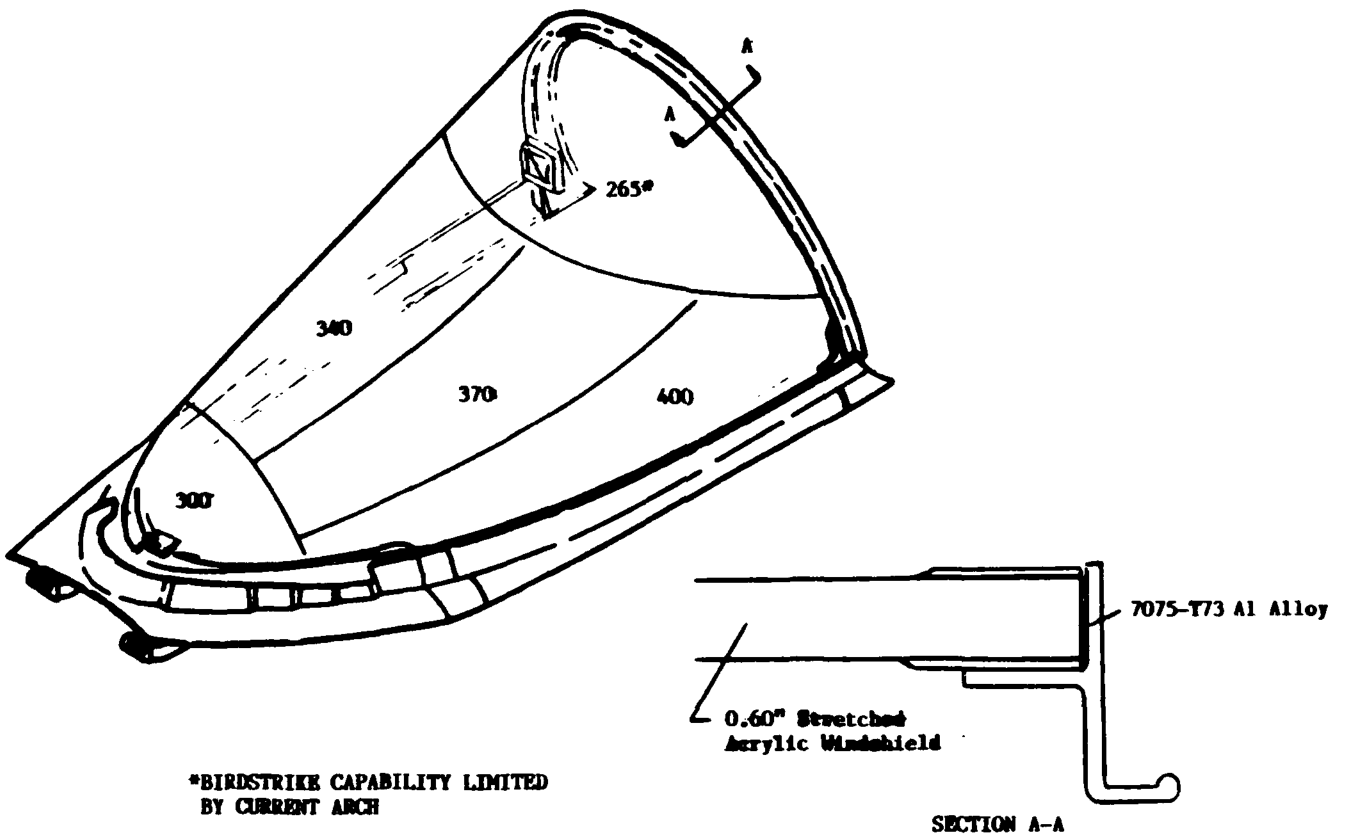


Figure 4. Estimated F-18 Birdstrike Resistance Capability.

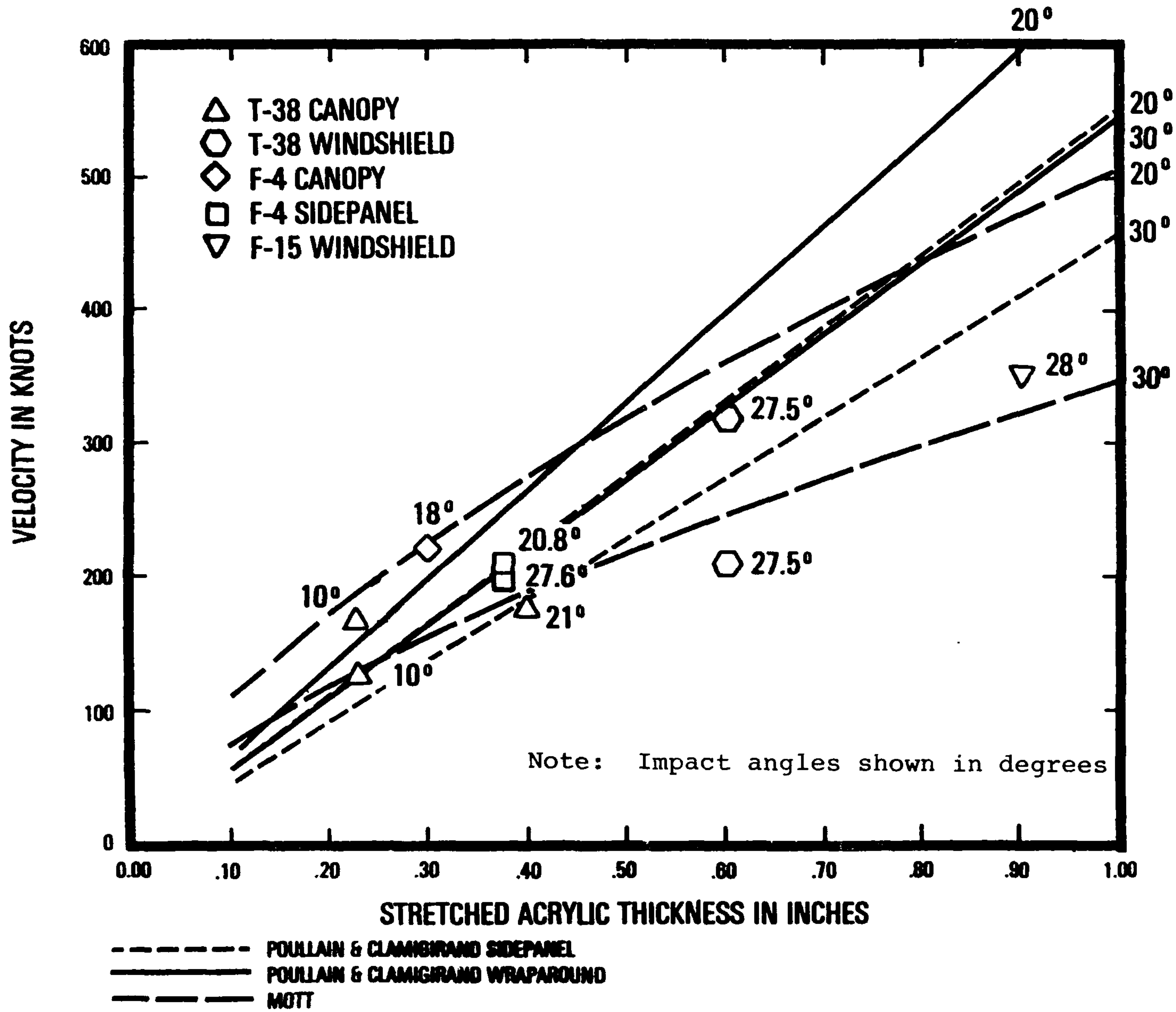


Figure 5. Summary of Parametric Equations and Test Data Points for Stretched Acrylic. Ref. 1,2,3.

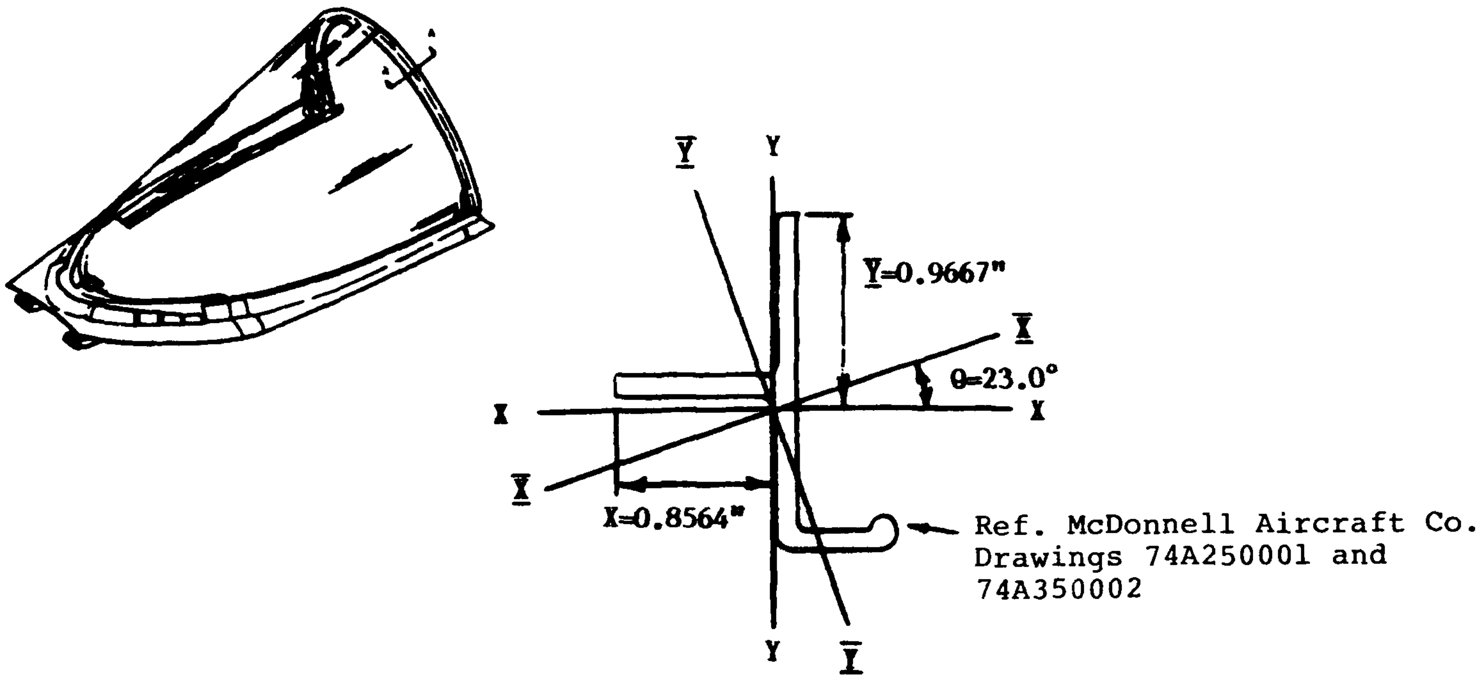
estimated that the F-18 would have a higher capability than the T-38 because it has a lower bird impact angle (24° versus 27.5°) and a more continuous transparency edge attachment (the stretched acrylic T-38 transparency was mounted to a nylon attachment which bolted to the frame, Reference 4) whereas the F-18 acrylic transparency was bolted directly to the frame. In addition, the 7075-T6 aluminum F-18 transparency frame is stronger and stiffer than the cast magnesium T-38 frame, thus providing better support to the transparency. The 7075-T6 Al is more than twice as strong and the modulus of elasticity is 60% greater than the magnesium casting.

It was estimated that the 3.5° decrease in the impact angle over the T-38 resulted in an increase of 20 knots in the impact capability; the remaining difference was expected as a result of an improved edge attachment and arch design (Reference 1).

The current F-18 production aft arch is fabricated from 7075-T73 aluminum and has the section properties shown in Figure 6. The birdstrike resistance capability of this arch was estimated by comparing it to the T-38 and F-4 test results (References 2 and 3). Figure 7 shows a plot of stress (measured using strain gages at the failure location) versus velocity for various tests conducted on the F-4 aircraft. AEDC test numbers have been shown for each F-4 data point. A curve, based on the structural and geometric properties, was fit to the test data points. Using the structural and geometric properties for the T-38, another curve was generated. This curve passes through the point which corresponds to failure of the arch as determined from birdstrike testing.

Because of the similarity between these transparency systems, a high level of confidence was placed on the estimated birdstrike capability of the F-18 windshield frame. An F-18 curve, based on its structural and geometric properties, was

F-18 AFT WINDSHIELD ARCH



$I_{\overline{XX}} = 0.1143 \text{ in.}^4$
$I_{\overline{YY}} = 0.0373 \text{ in.}^4$
$I_{XY} = -0.0277 \text{ in.}^4$

$I_{XX} = 0.1025 \text{ in.}^4$
$I_{YY} = 0.0491 \text{ in.}^4$
$\text{AREA} = 0.4656 \text{ in.}^2$

Figure 6. Section Properties of Aft Windshield Arch.

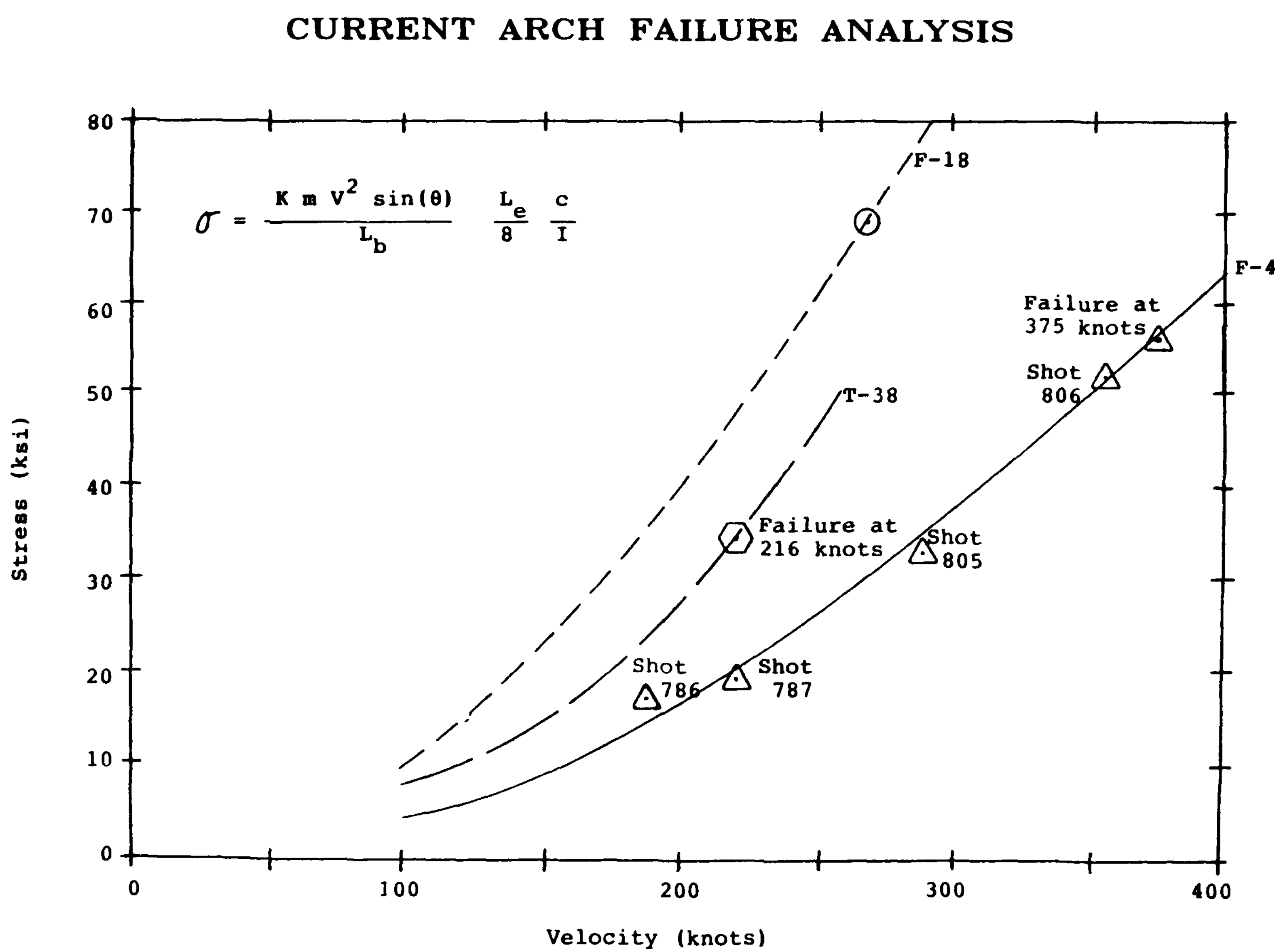


Figure 7. Plot of Aft Arch Outer Fiber Bending Stress vs. Velocity (Ref. 3).

plotted as shown in on Figure 7. At approximately 265 knots, the stress in the arch was estimated to be equal to the ultimate strength of the material and is, therefore, the predicted capability.

A major problem with each of these production windshield frames (F-4, T-38 and F-18) is that the transparency support structure lacks sufficient toughness which results in the system failing catastrophically when impacted above the threshold velocity.

SECTION 4

IDENTIFICATION OF ALTERNATE WINDSHIELD SYSTEMS

Alternate windshield system designs were selected by UDRI in conjunction with AFWAL/FIEA. In past programs, UDRI had worked in conjunction with major transparency suppliers to select alternate transparency systems. Now, however, because of the experience gained from these past programs, UDRI and AFWAL have a considerable database from which to select alternate systems. Alternate systems were based on this combined experience of AFWAL and UDRI, and on the guidelines and constraints which governed this study. The current monolithic stretched acrylic transparency provides good serviceability and life; however, increased bird impact resistance results in an increase in the acrylic thickness, resulting in a relatively heavy transparency. When impacted only slightly above the capability, acrylic materials tend to fail catastrophically (References 1,2,3,5,6).

The McDonnell Aircraft Company proposed a 0.94-inch thick stretched acrylic windshield with a redesigned frame which was to have 500 knot capability as a developmental goal (Reference 7). This was the thickest monolithic stretched acrylic transparency that could be formed and still meet the optical requirements. It was believed by UDRI that the highest capability that could be attained with this system would be about 475 knots (reference Figure 5) and that considerable development effort would be required to attain this capability at the critical locations.

Monolithic polycarbonate has been used in the past on the F-16 aircraft. Bare polycarbonate cannot be used because of its low durability--being susceptible to surface abrasion and UV/environmental degradation. To date, there have been durability problems with the coated polycarbonate materials

(Reference 8). New generation coatings, currently being flight-tested on the T-38 aircraft, may provide adequate durability; however, these materials must be thoroughly evaluated and tested before they can be put into production. Another problem with monolithic polycarbonate is the embrittling effect of minor surface imperfections (Reference 9). Small imperfections can result in a catastrophic failure of the transparency at velocities much lower than the established capability. Multiple plies of polycarbonate minimize the possibility of a single flaw resulting in failure, which in the case of a monolithic polycarbonate ply would be catastrophic.

In general, available test data indicates that laminated polycarbonate panels, combined with an acrylic outer face ply and separated by low modulus ductile interlayers, offer high strength/weight performance for bird impact. The opportunities to vary stiffness and strength and thus performance are almost limitless. One may depart from symmetric laminates and vary the thickness of the structural plies and the thickness and material properties of the interlayers. Laminated configurations also facilitate the incorporation of electrically conductive coatings for deicing and threat suppression capability. Laminated acrylic/polycarbonate transparency designs can provide an increased level of bird impact resistance over the current stretched acrylic windshield system without an increase in weight. The acrylic surface plies provide protection for the polycarbonate, the main structural ply of the system. Maintenance of the outer acrylic surface would be the same as the current transparency. A range of thicknesses, corresponding to a range in bird impact resistance, of the laminated transparencies were evaluated.

In all transparency systems, the edge attachment is critical for bird impact occurring near the panel edge. The

importance of considering total system response, edge member cross-section, and the details of edge member attachment are clearly demonstrated in References 1 through 6 and 10 through 15.

Seven transparency alternatives and four frame alternatives were identified; each representing a major trade-off between birdstrike protection, weight, cost, visibility and durability. Below are listed each of the transparency and frame alternatives.

Transparency Alternatives

- Coated monolithic polycarbonate - total thickness 0.6 inches.
- Two plies of laminated polycarbonate separated by a low modulus interlayer and coated on the interior and exterior surfaces - total thickness 0.6 inches.
- Two plies of laminated polycarbonate with an exterior ply of acrylic and an interior coating; plies to be separated by a low modulus interlayer - total thickness 0.6 inches.
- Monolithic stretched acrylic - total thickness 0.94 inches (Reference 7).
- Two plies of laminated polycarbonate with an exterior ply of acrylic and an interior coating; plies to be separated by a low modulus interlayer - total thickness 0.66 inches.
- Two plies of laminated polycarbonate with an exterior ply of acrylic and an interior coating. Plies to be separated by a low modulus interlayer - total thickness 0.73 inches.

- Two plies of laminated polycarbonate with both an exterior and interior ply of acrylic; plies to be separated by a low modulus interlayer - total thickness 0.84 inches.

Frame Alternatives

- Current aluminum frame with new composite aft arch.
- Current aluminum frame with new titanium aft arch.
- Current aluminum frame with reinforced aft arch.
- New redesigned aluminum frame for the 0.94-inch-thick acrylic transparency (Reference 7).

SECTION 5

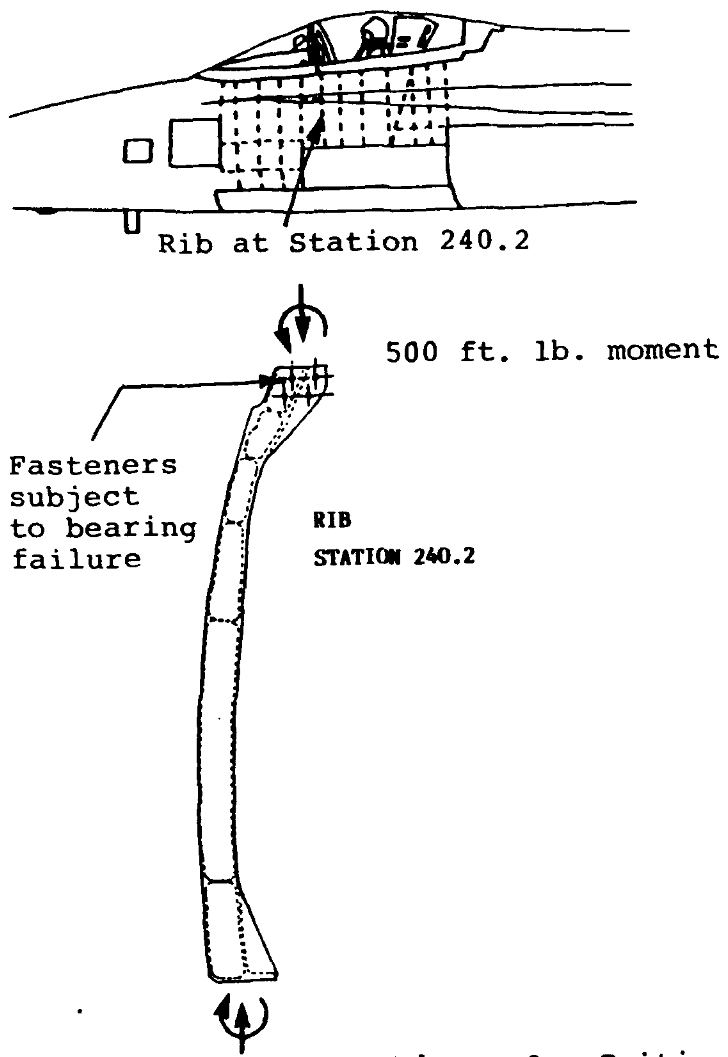
ESTIMATED BIRDSTRIKE CAPABILITIES OF ALTERNATE WINDSHIELD SYSTEMS

The alternate transparency systems were evaluated to determine the bird impact capabilities of each system. Each estimated system capability was based on the estimated capability of each transparency (this assumed that the transparency support structure would be designed to optimize the transparency performance). The bird impact capability of each alternate transparency was estimated using parametric equations in conjunction with the results of bird impact tests conducted on similar transparency systems. As part of this effort, the strength of the fuselage structure which supports the transparency was also evaluated.

The analysis of the F-18 critical windshield system support structure is contained in Appendix A. This analysis evaluated the fuselage structure which reacts the loads resulting from a birdstrike on the windshield. The analysis included the following structure: upper longeron, ribs at station 233.7 and 240.2, effective skin, and critical fasteners. The most critical component was found to be the rib at station 240.2. The three possible failure modes and corresponding loads are shown in Figure 8.

The fuselage station 240.2 rib was analyzed as follows to determine the peak vertical (axial) load carrying capability. A constant 500 ft-lb moment was assumed at the ends of the rib when the axial load capability was calculated. This moment would be applied to the upper longeron and rib through the base of the aft windshield arch. The magnitude of the moment was based on finite analyses of birdstrike resistant transparency systems having a similar geometry and a bird impact capability of about 500 knots. Crippling failure of the rib occurs at just over a 5,000 lb axial

FUSELAGE CRITICAL STRUCTURE



Critical Fuselage Structure

Maximum Allowable Birdstrike Load

Crippling Failure:	5690 lbs.
Buckling Failure:	9752 lbs.
Bearing Load Failure:	7020 lbs.

Figure 8. Critical Fuselage Structure.

load. This failure was not considered critical because at the onset of crippling the load would redistribute into adjacent structure, minimizing damage. This type of damage would not prevent the aircraft from returning to the base.

Bearing failure of the fasteners which connect the rib to the upper longeron occurs at a load of about 7,000 pounds. Failure of these fasteners results in loss of the applied moment (500 ft-lbs), and without this moment the rib would buckle at a 2,000 to 3,000-pound load. This failure could cause loss of aircraft control if critical aircraft flight controls were located in this area. This was discussed with NAVAIR and it was concluded that no critical flight controls were located in this area and therefore this type of failure would not pose a flight safety risk.

In order to determine the velocity at which fuselage failure could occur, a family of vertical sill load versus birdstrike impact velocity curves was generated for various fighter aircraft (reference Figure 9). The failure points for the F-4 and T-38 aircraft were based on experimental test results and were used as input in generating the curves.

Since these curves were tightly bounded, a relatively high level of confidence was placed on the sill load that was predicted for a given birdstrike velocity. The F-18 curve predicts a 7,000 lb sill load at about 475 knots. A transparency system for the F-18 having a birdstrike capability higher than 475 knots may result in damage to the fuselage or require some fuselage modification to prevent failure of the fuselage.

The transparency capability for each alternate transparency system was estimated using parametric equations and experimental test results from aircraft with similar transparency systems. The results of the parametric equations for a 4-pound bird impacting a center location at 24° have been summarized on Figure

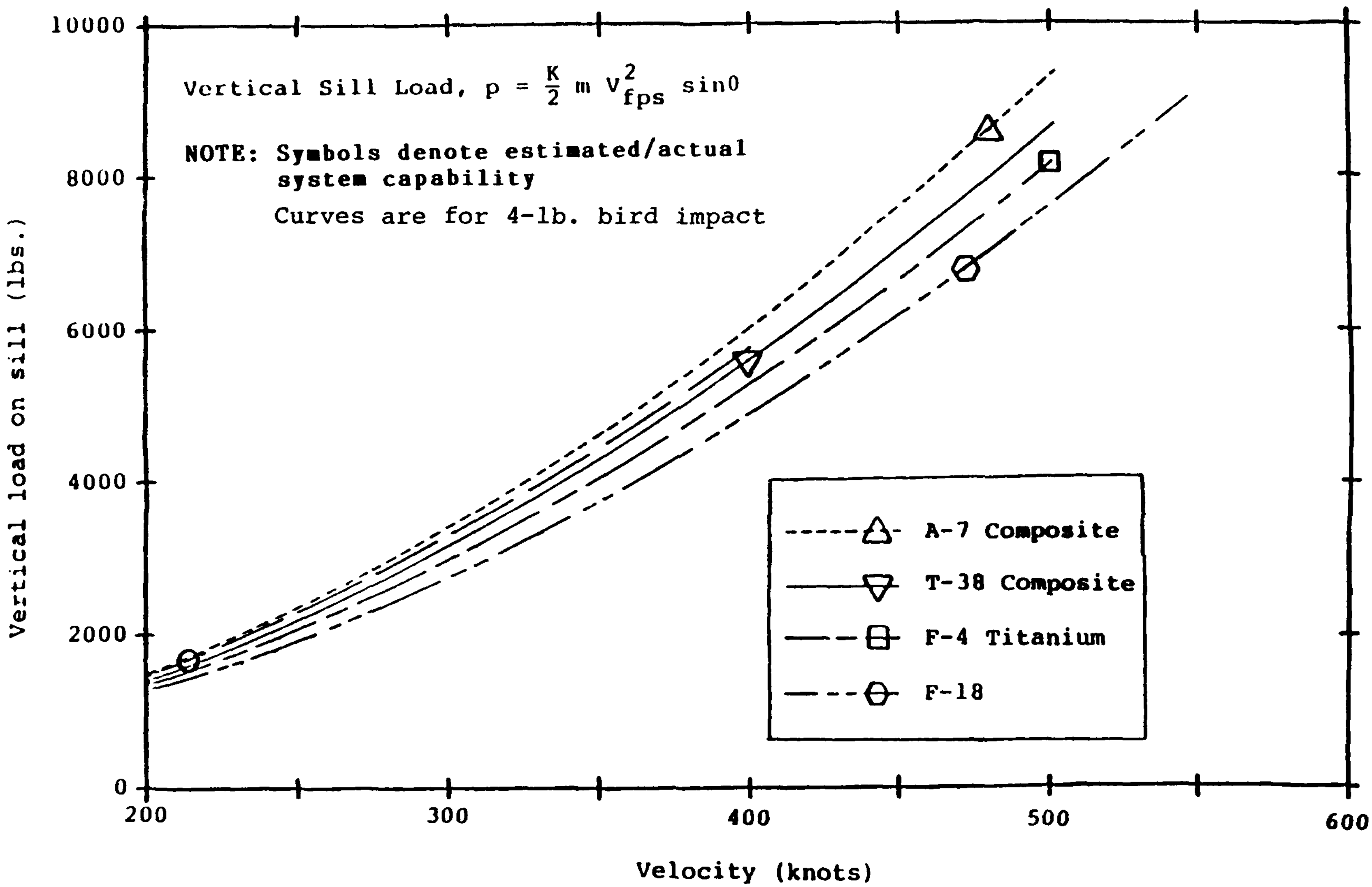


Figure 9. Vertical Sill Load vs. Impact Velocity.

10. This range is based on curves by Ingelse & Wintermute (Ref. 6), Bosik-Bolted Edge Attachment (Ref. 1), Rockwell (Ref. 1), Goodyear Aerospace Corp. (Ref. 1), and West and Clayton (Ref. 4). The predicted penetration velocity for the various equations diverge at higher velocities (greater thicknesses). Several reasons for this divergence are as follows:

- First, the transparency edge condition becomes more critical at higher velocities making it difficult to accurately predict the birdstrike capability.
- Second, the thicker the transparency, the more the transparency cross section can vary, which further increases the range of capability.
- Third, variations in the overall windshield geometry (i.e., overall size and single or double curvature) can have a significant effect on the birdstrike capability.

Confidence in, and accuracy of, the estimated capabilities were increased by using the birdstrike test results from similar aircraft systems; actual capabilities being compared to the estimated capabilities. Experimental birdstrike test results for various aircraft transparency systems have been summarized on Figure 11. These actual capabilities were used to substantiate and make adjustments for overall geometry, edge conditions, etc. to the parametric equations (Figure 10) to more accurately evaluate F-18 alternate transparency systems. For example, the T-38 windshield has about the same thickness and impact angle as the F-4 side panel; however, the T-38 capability is about 400 knots where as the F-4 side panel has 500-knot capability. This is a significant difference due entirely to panel geometry--not accounted for in the parametric equations. This example

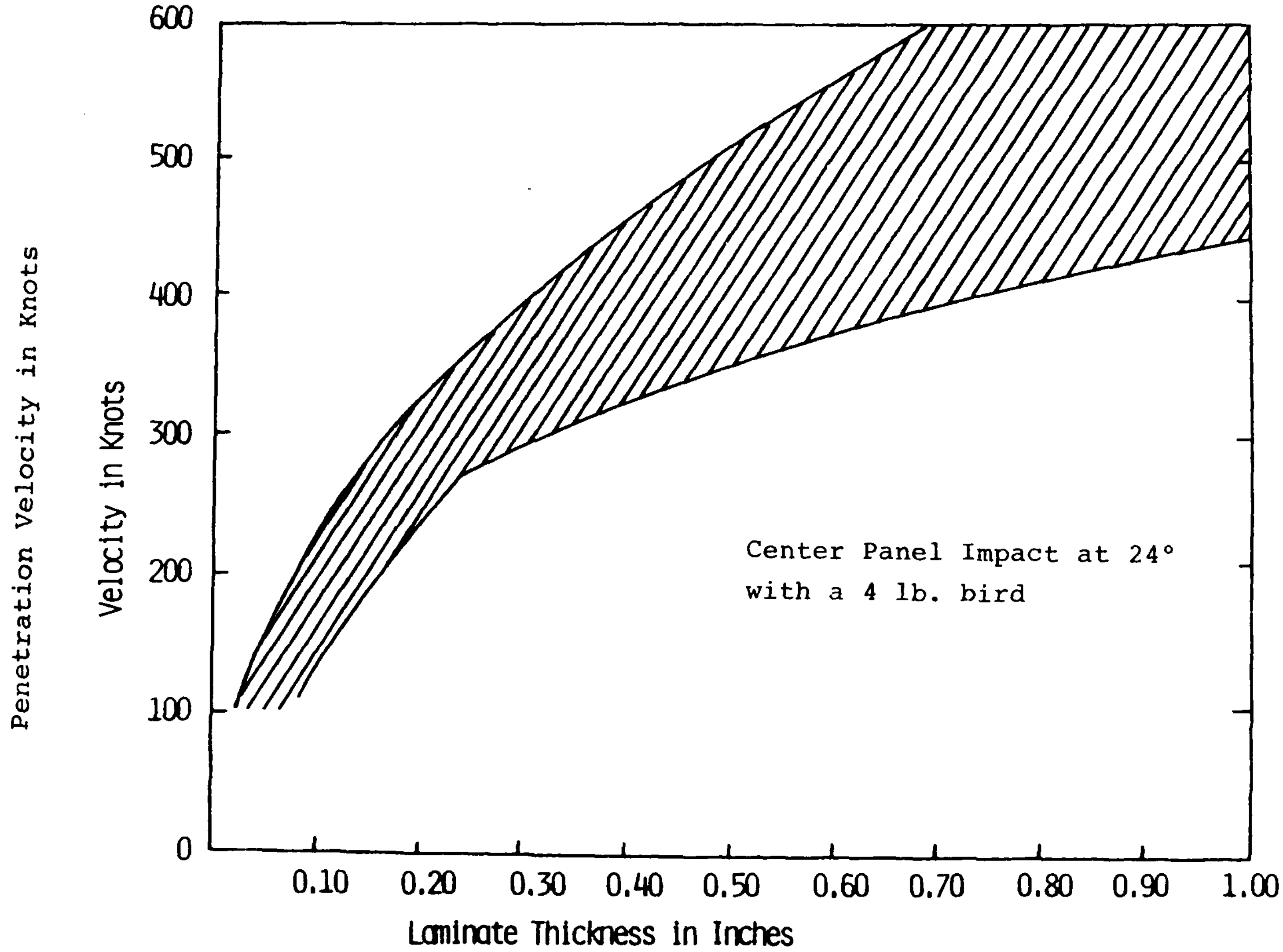


Figure 10. Theoretical Thickness versus Velocity Curves for Laminated Polycarbonate.

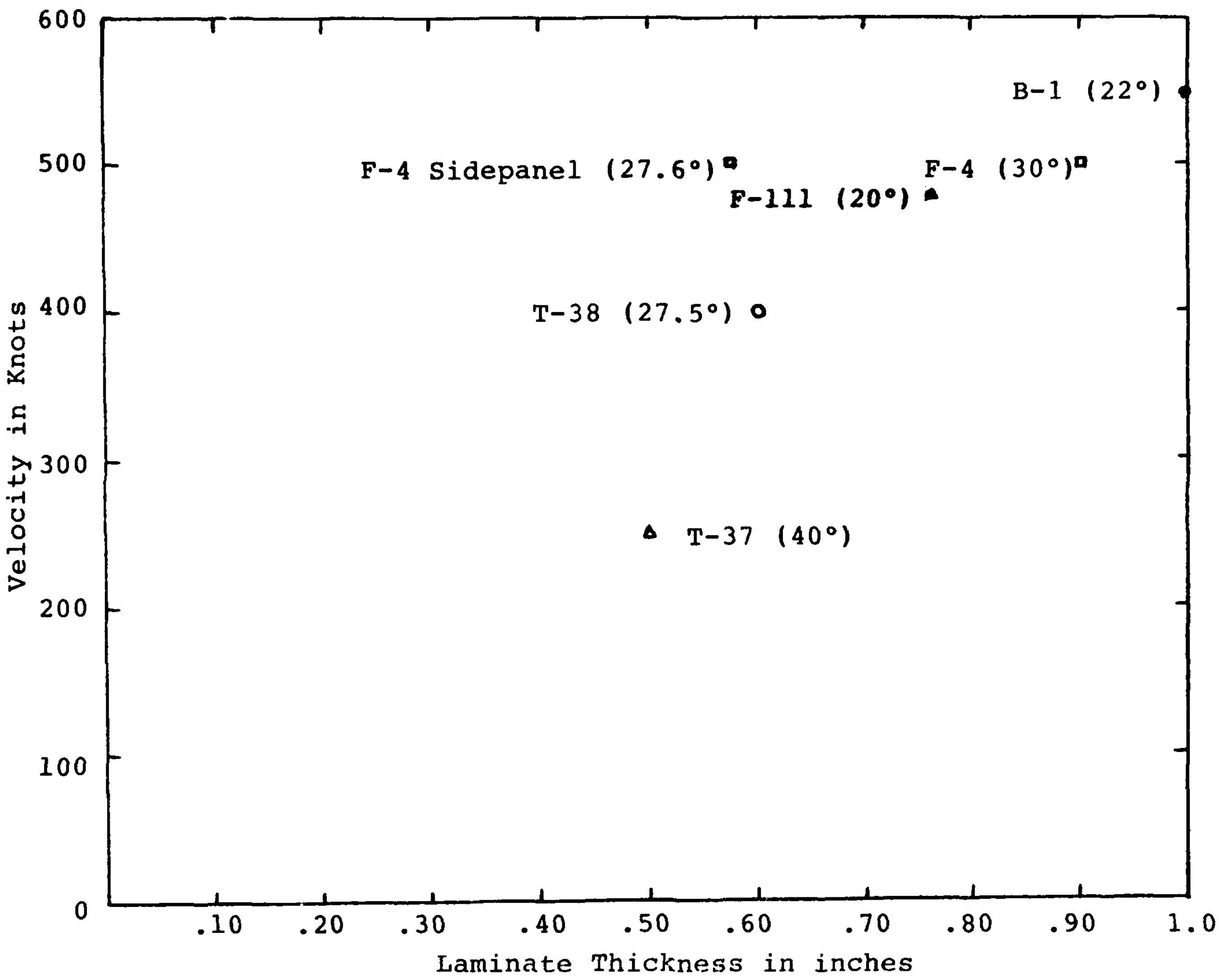


Figure 11. Summary of Capabilities Based on Birdstrike Tests.

demonstrates the need to include available relevant experimental data when evaluating system birdstrike capability.

The estimated capabilities for the F-18 alternate transparency systems have been summarized on Figure 12, 13 and 14. Figure 12 shows two 0.6-inch-thick polycarbonate transparencies with a coated interior and exterior surfaces. These transparencies would weigh about the same as the current system and increase the birdstrike capability by over 60 percent. In the past, materials with outer surface coatings have exhibited durability and maintenance problems (e.g., embrittling the polycarbonate, loss of coating adhesion, difficulty to repair in the field, etc.). New coatings, yet to be used in production, may prove to have much improved durability over currently used materials. At this time, new coatings are being evaluated in the prototype stage but are yet to be qualified in production.

Four laminated acrylic/polycarbonate transparencies were evaluated (Figures 13 and 14). These transparencies offer different levels of bird impact resistance capability. This basic design has been proven in service for over nine years. A 0.6-inch-thick transparency would provide 450-knot capability; a 0.66-inch-thick transparency would provide 475-knot capability, and 0.73-inch-thick transparency would provide 500-knot capability. The 0.84-inch-thick design has both exterior and interior acrylic plies and a bird impact capability of about 540 knots.

A 0.94-inch-thick stretched acrylic transparency is shown in Figure 14. This transparency would require an R&D program to achieve this level of protection (Reference 7). The best acrylic windshield edge attachment design would allow the transparency to have a capability near the forward and aft edges to approach the capability at the center of the panel. An inherent problem with

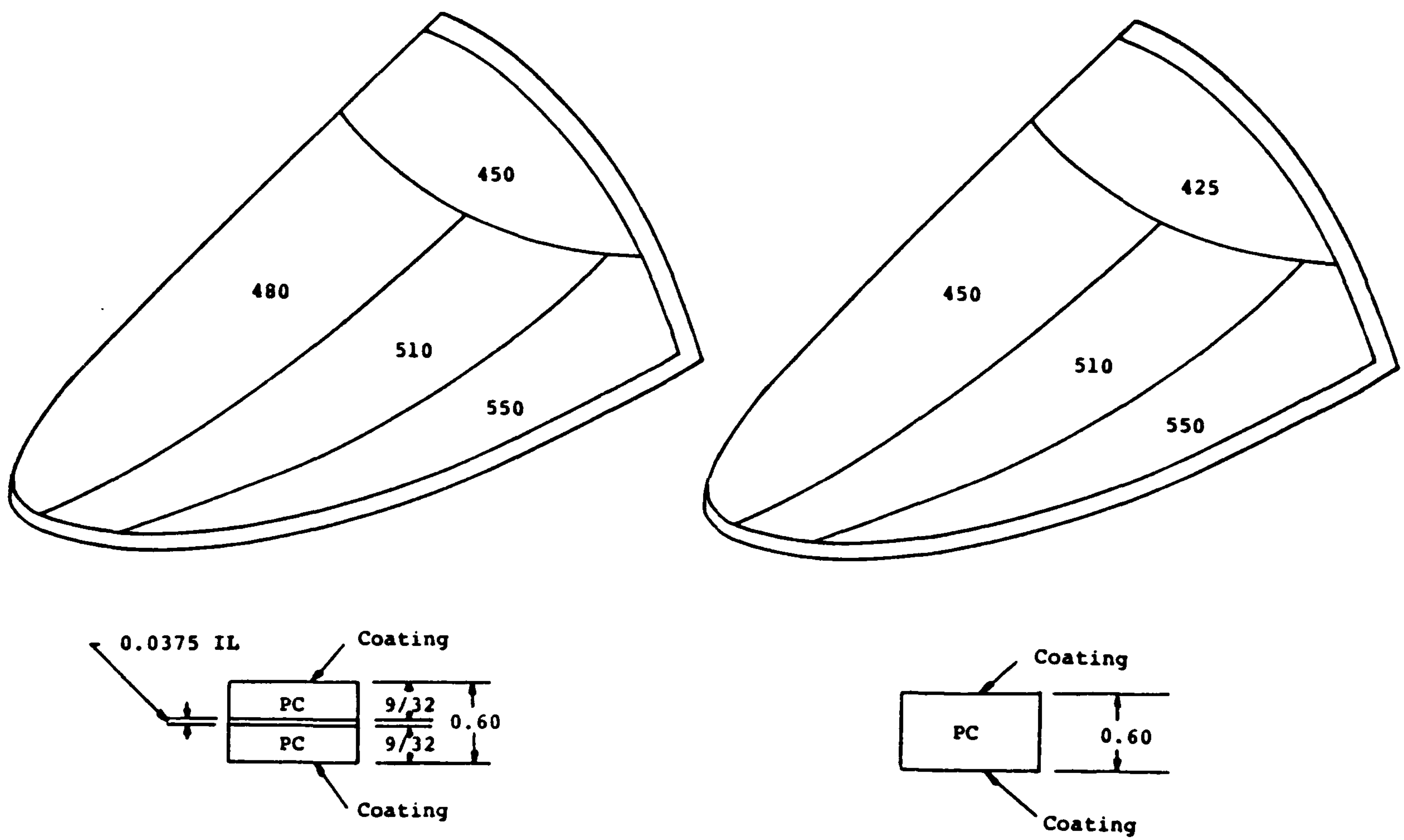


Figure 12. Alternate Transparencies Having a Coated Polycarbonate Exterior Surface.

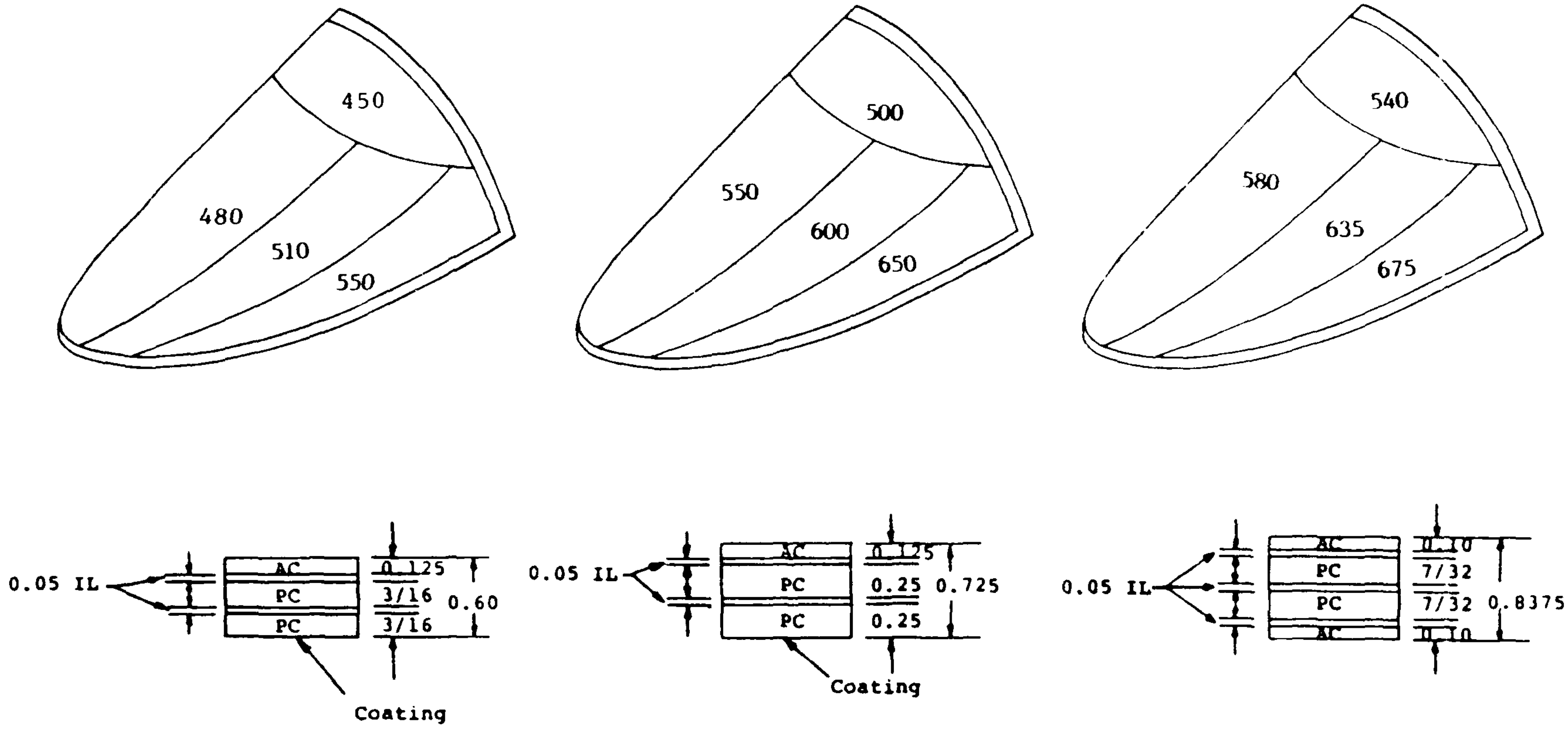


Figure 13. Alternate Transparencies Which are a Laminated Acrylic/Polycarbonate.

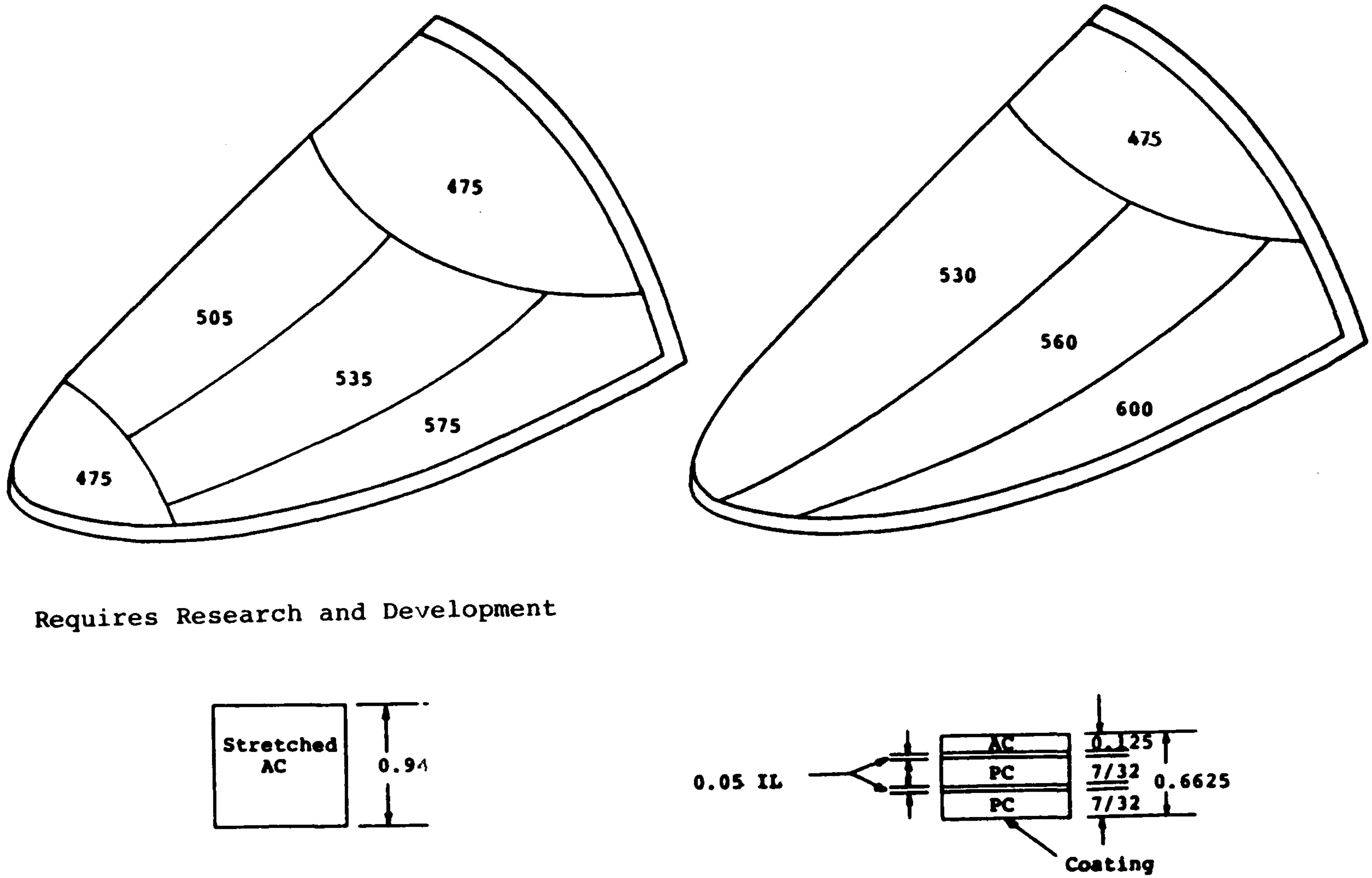


Figure 14. Alternate Transparencies Having a 475 Knot Birdstrike Resistance Capability.

acrylic transparencies is that impacts above the threshold capability result in catastrophic failure and potentially lethal spall enters the cockpit (References 12, 13).

SECTION 6
BIRDSTRIKE RISK ASSESSMENT

The birdstrike probability risk assessment was conducted to provide statistical data concerning the effect of alternate levels of bird impact resistance on the number of penetrating birdstrikes. Six models, representing the six alternate transparency capabilities (see Figures 12, 13, and 14) were constructed and analyzed. The aircraft history, see Figure 15, is used to validate this analysis. The analysis predicts the number of penetrating birdstrikes over a 10-year period. Because of unknown future changes in the number of in-service aircraft and mission profiles, the analysis may not accurately represent the total number of penetrating birdstrikes. However, the predicted percent reduction in the number of future penetrating birdstrikes per low level flight hour for an alternate windshield system will be representative of the actual reduction.

The birdstrike probability program has been used to evaluate the relative performance of aircraft transparency systems in terms of birdstrike resistance. The probability of a birdstrike causing damage (penetration) on a system can be evaluated and the total number of birdstrikes and penetrations for a given number of flight hours can be calculated. This program is most useful as a tool for comparing relative performance of different transparency systems for a given aircraft. Because of the uncertainty involved in the input data, the penetration numbers generated by this program should not be considered in any way absolute and are only as good as the input. A complete description of the mathematical theory is contained in

YEAR	NUMBER REPORTED	CREW INJURIES	FLIGHT MODE/ ALTITUDE	COMMENTS
1983	3	--	LOW LEVEL/500'	
		--	TAKE OFF/200'	STARLING
		--	LANDING/0'	SMALL BIRD
1984	3	--	LANDING/50'	SMALL BIRD
		--	DESCENT/3000'	MEDIUM BIRD
		MINOR	LOW LEVEL/600'	420 kts., 4.5 lb. TURKEY BUZZARD
1985	3	--	TAKE OFF/200'	SMALL BIRD
		--	CRUISE/3000'	185 kts., 2 lb. BIRD
		--	CRUISE/3000'	DAMAGED WINDSCREEN EDGING STRIP

Figure 15. Summary of F-18 Birdstrikes.

Reference 16 and a detailed description of how to use the program is contained in Reference 17.

The Birdstrike Risk Assessment program mathematically models the real world by using a given bird density per cubic mile, determining the volume of space swept out by the aircraft windshield using the windshield frontal area, time in the bird environment, and mean velocity in the bird environment, and then calculating the total birdstrikes. The number of birdstrikes, N< is calculated by

$$N = \rho A \bar{V}_{avg} T_{5000} \qquad \text{Reference 17} \qquad (1)$$

ρ = bird density/cubic mile

V_{avg} = average aircraft velocity in the bird environment

T_{5000} = time spent below 5000 ft AGL (in the bird environment

The average aircraft velocity and time below 5000 ft was provided by NAVAIR, and the frontal area (485 in^2) was determined from the design drawings. In past programs, the bird density was estimated by the size and types of birds that impacted the specific aircraft. However, in the case of the F-18, which has a relatively short in-service history, this was not possible. As a result, the bird density for the entire F-4 fleet (2.862 bird/$miles^3$) was used (Reference 3).

The analysis was conducted for F-18's using an average of 360 flight hours per aircraft per year with 35 percent of this time, or 126 hours, in the bird environment. An average fleet size (over the next 10 years) of 683 aircraft was used. The predicted number of penetrations is obtained by multiplying the total number of birdstrikes by the probability of damage.

The probability of damage is calculated as follows: The unconditional probability that a random birdstrike will be damaging can be expressed as:

$$P(D) = \int_0^\infty h(K)\ P(D/K)\ dK \qquad \text{Reference 17}$$

where h(K) is the probability density function of impacting kinetic energies which is based on the birdweight distribution, aircraft velocity profile. P(D/K) is the transparency strength distribution function.

Birdweight distribution is obtained from Norton or BASH birdstrike data files for the particular military aircraft, or from specific studies of bird population weight distribution. From this data a birdweight cumulative distribution curve given by

$$P(w) = 1.0 - \exp(-w/B2)^{A2} \qquad \text{Reference 17}$$

is developed. The birdweight cumulative distribution curve used for the F-18 is shown in Figure 16 and is the same as that developed for the entire F-4 fleet.

The aircraft velocity profile in the bird environment can be obtained from projected or actual mission profile data, or from service life data. Note that only data from below 5,000 feet AGL should be used, because the bird population above 5,000 feet AGL is minimal. The aircraft velocity used for this analysis is shown in Figure 17 and was obtained through NAVAIR. Transparency strength distribution can be obtained from either birdstrike tests or it can be estimated. The estimated transparency strength distributions for the alternate windshield systems were used and are shown in Figures 18 through 25.

The results of the birdstrike risk assessment are summarized in Table 1. With the current monolithic acrylic

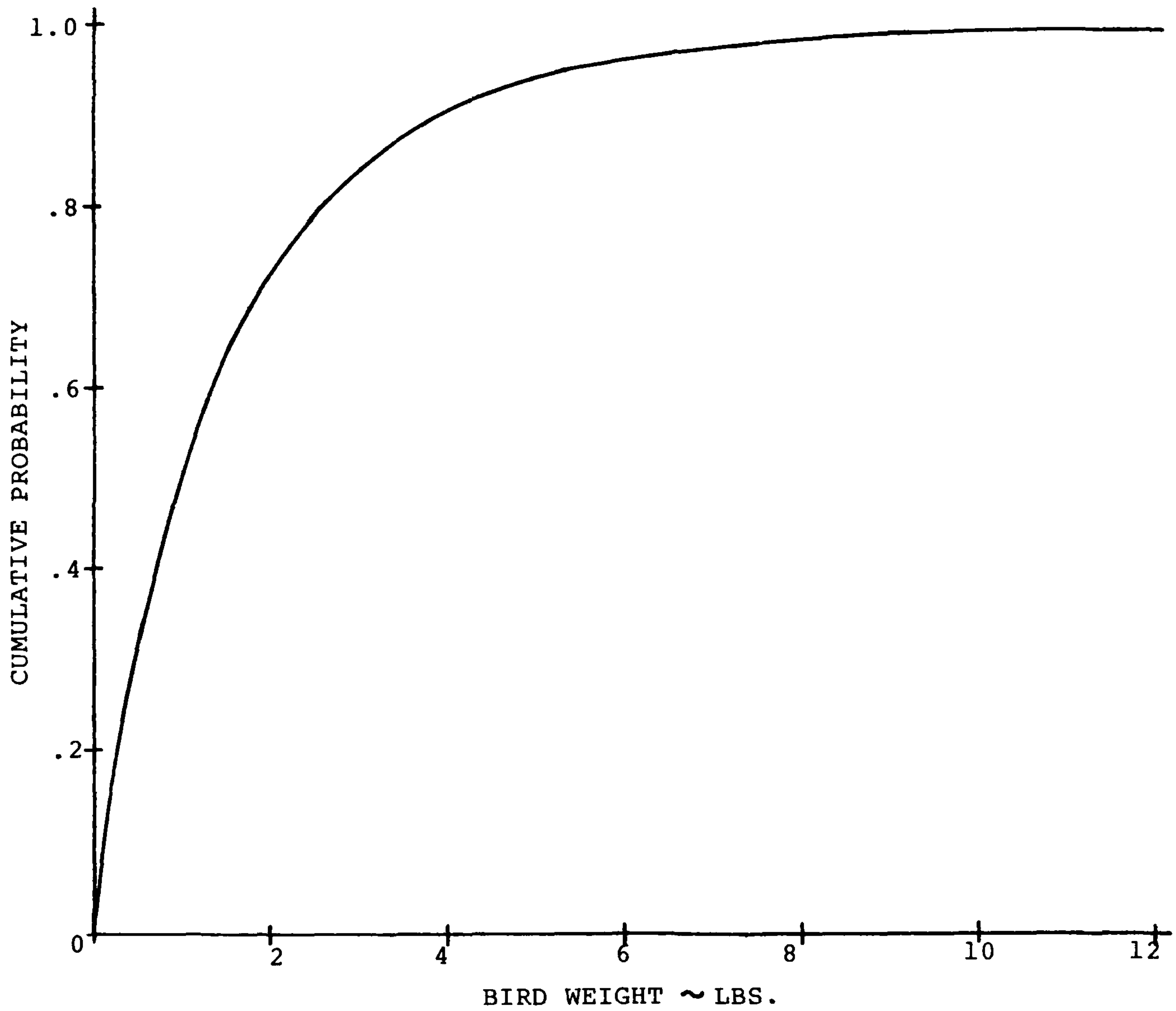


Figure 16. Birdweight Cumulative Distribution Curves G(W).

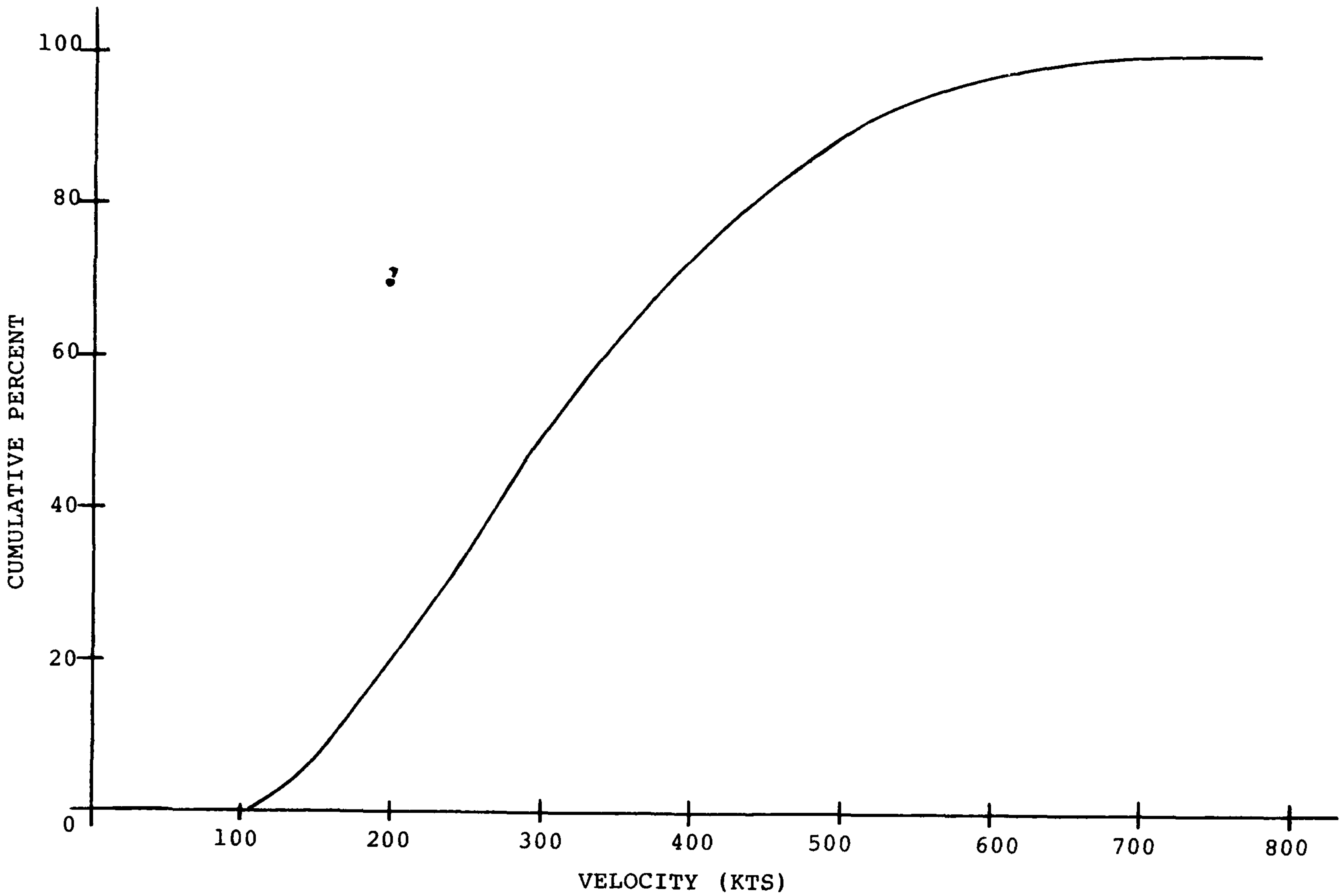


Figure 17. Velocity Cumulative Distribution for F-18 Aircraft.

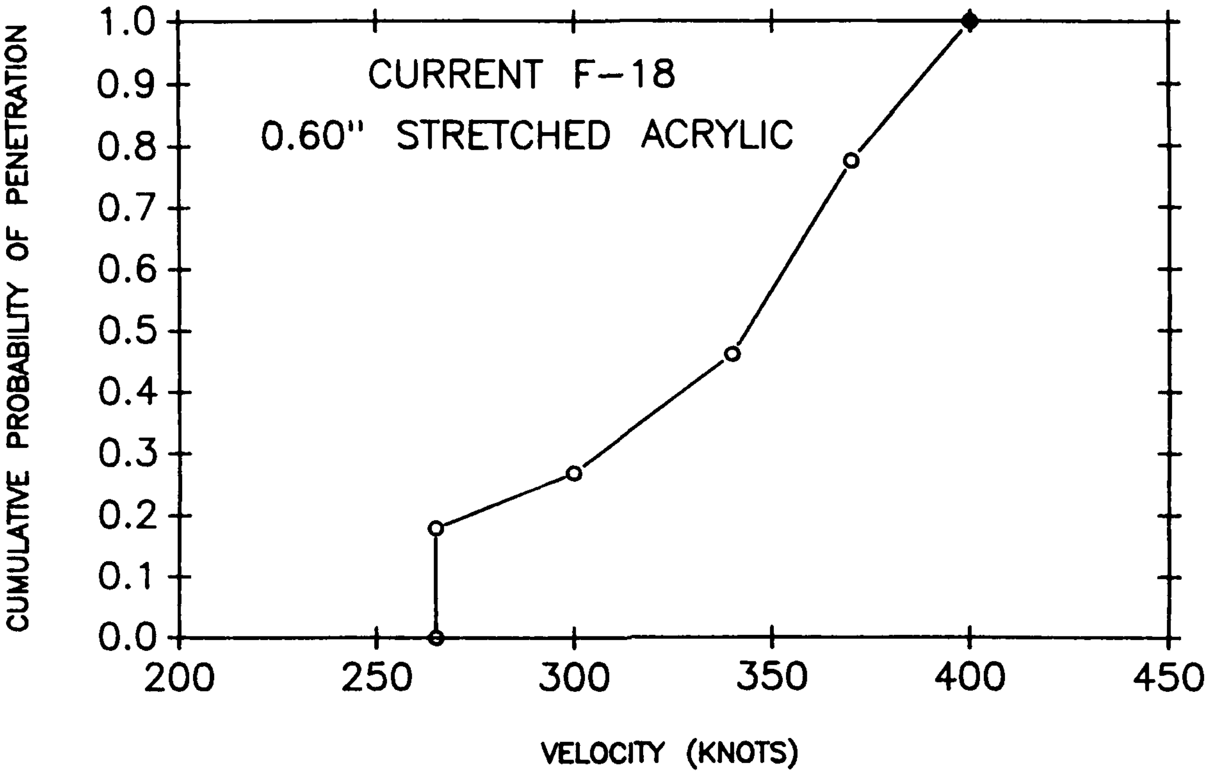


Figure 18. Windshield Strength Distribution Function, Current F-18 0.60" Stretched Acrylic.

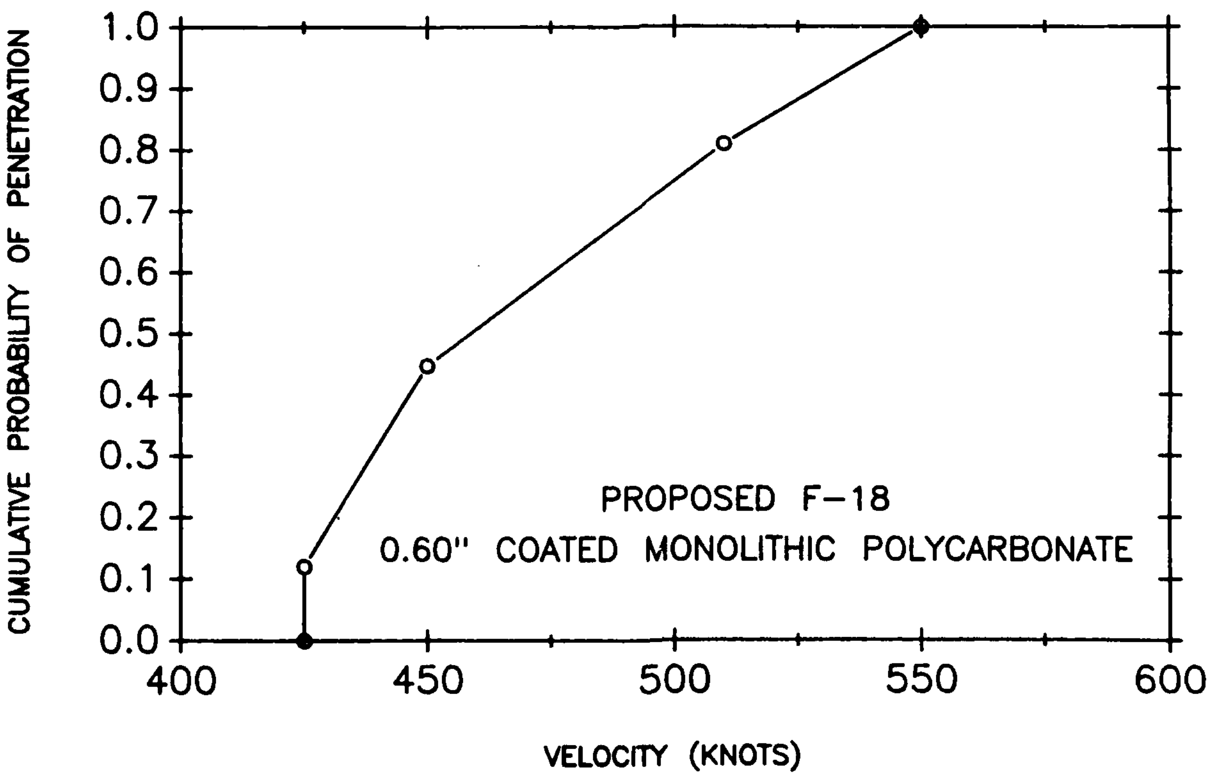


Figure 19. Windshield Strength Distribution Function, Proposed F-18 0.60" Coated Monolithic Polycarbonate.

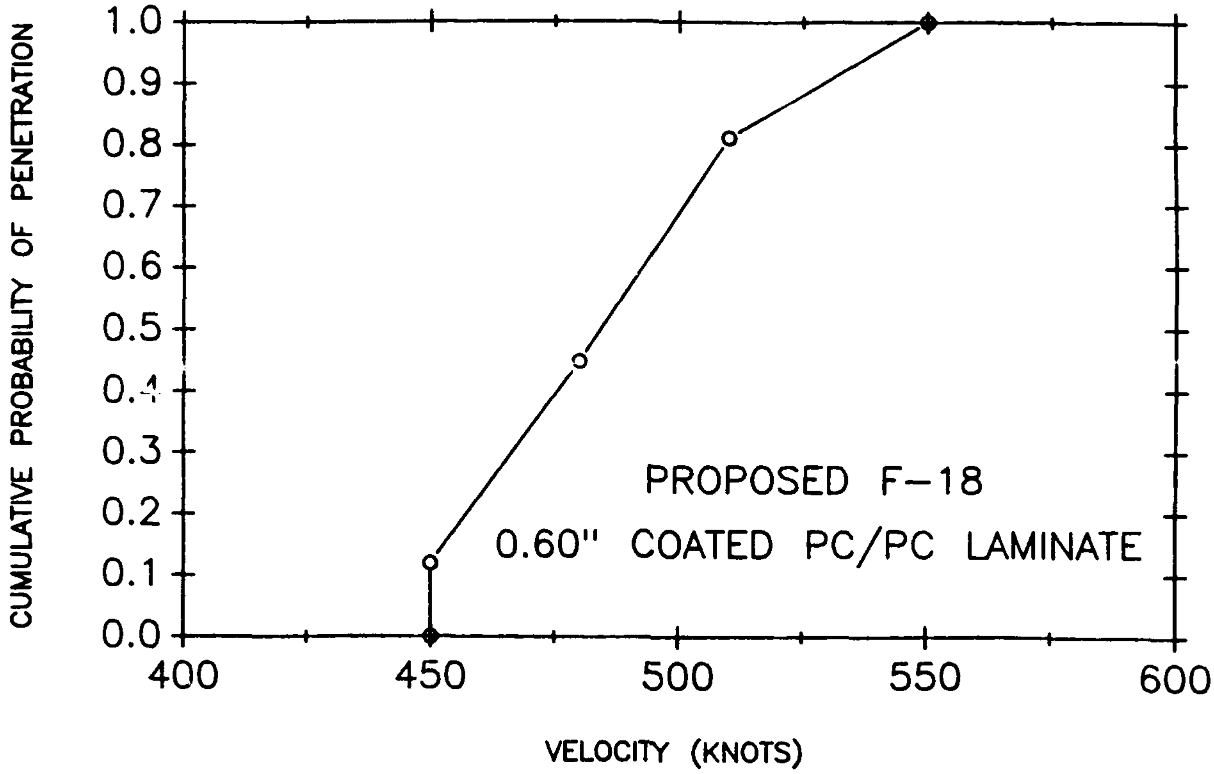


Figure 20. Windshield Strength Distribution Function, Proposed F-18 0.60" Coated PC/PC Laminate.

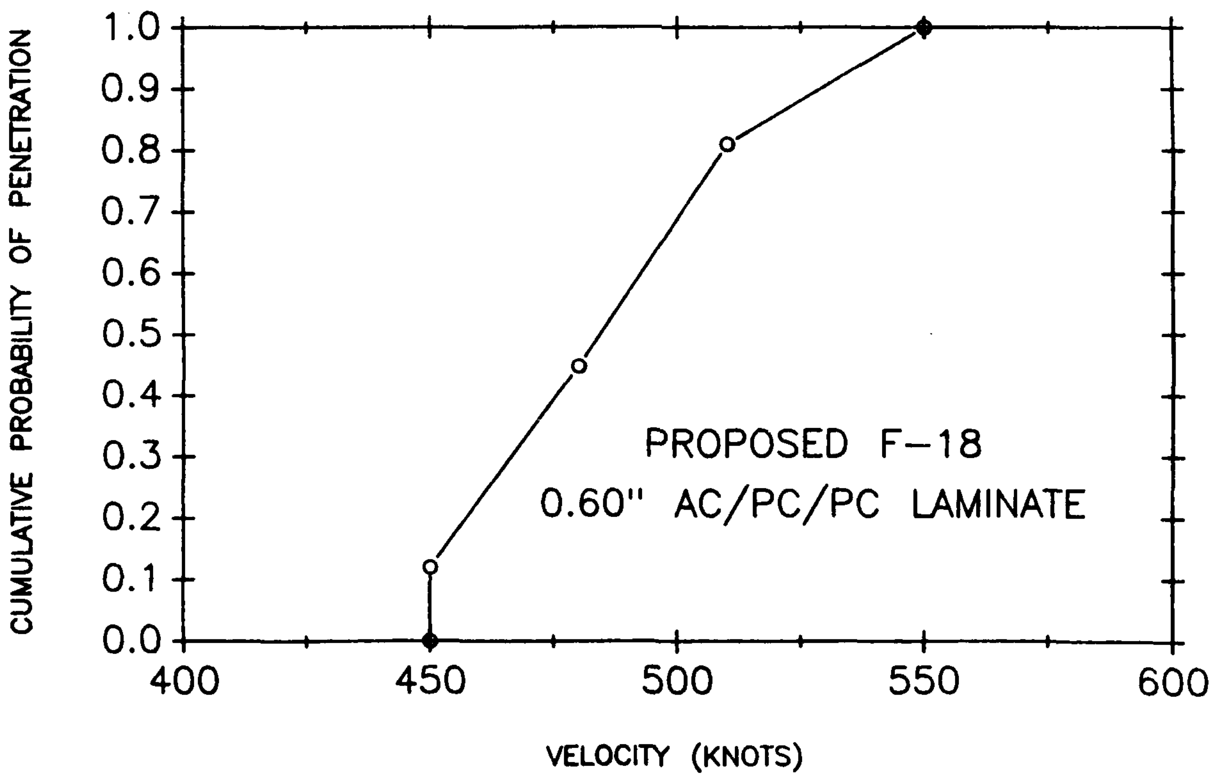


Figure 21. Windshield Strength Distribution Function, Proposed F-18 0.60" AC/PC/PC Laminate.

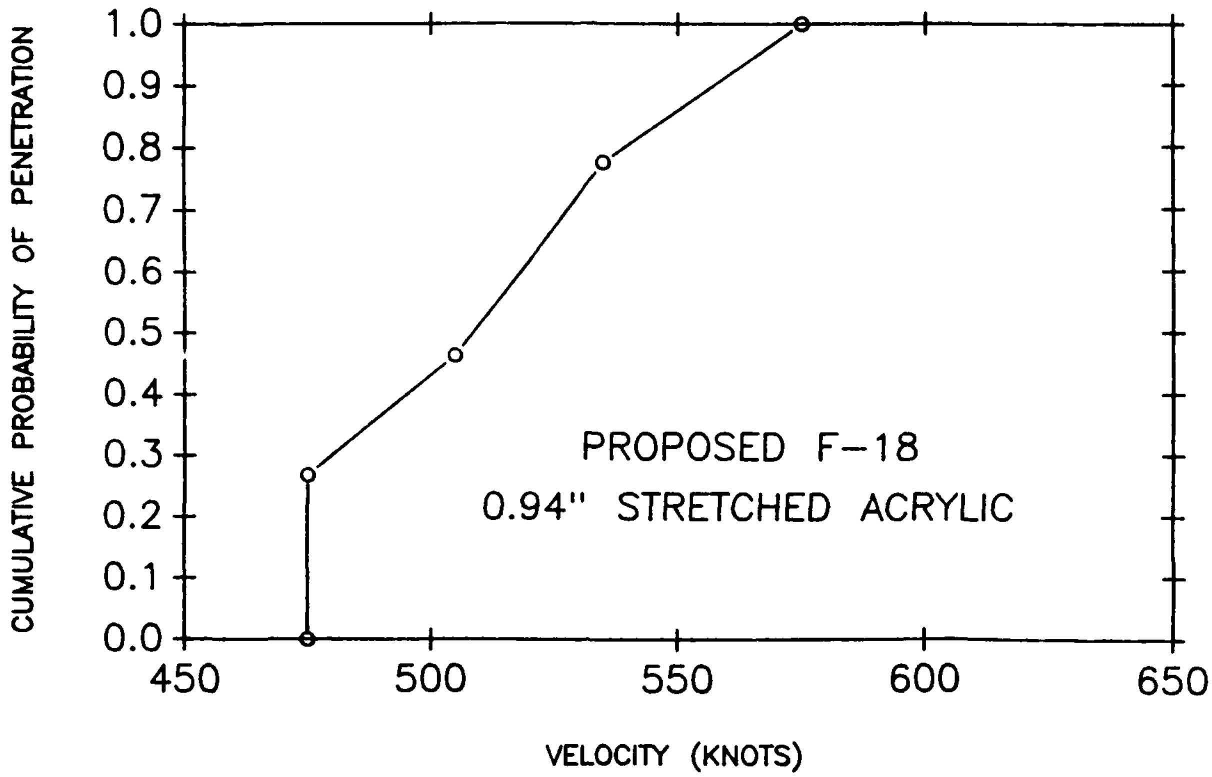


Figure 22. Windshield Strength Distribution Function, Proposed F-18 0.94" Stretched Acrylic.

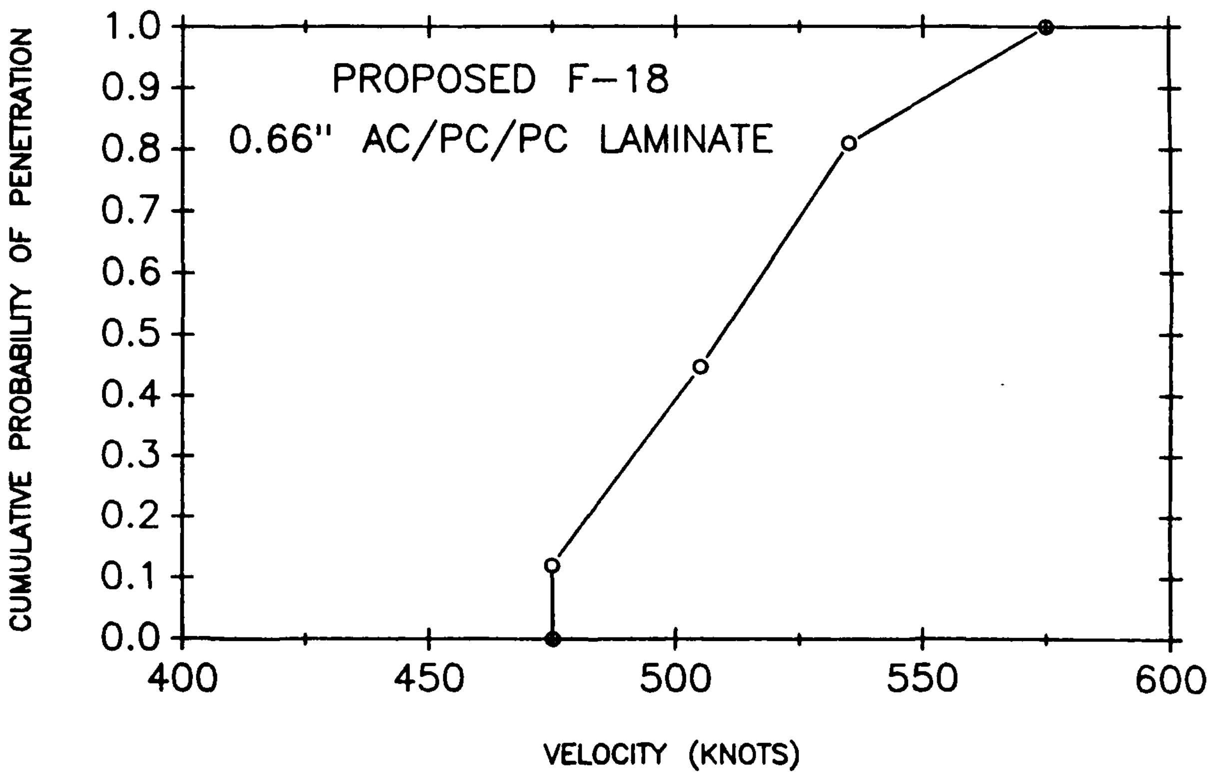


Figure 23. Windshield Strength Distribution Function, Proposed F-18 0.66" AC/PC/PC Laminate.

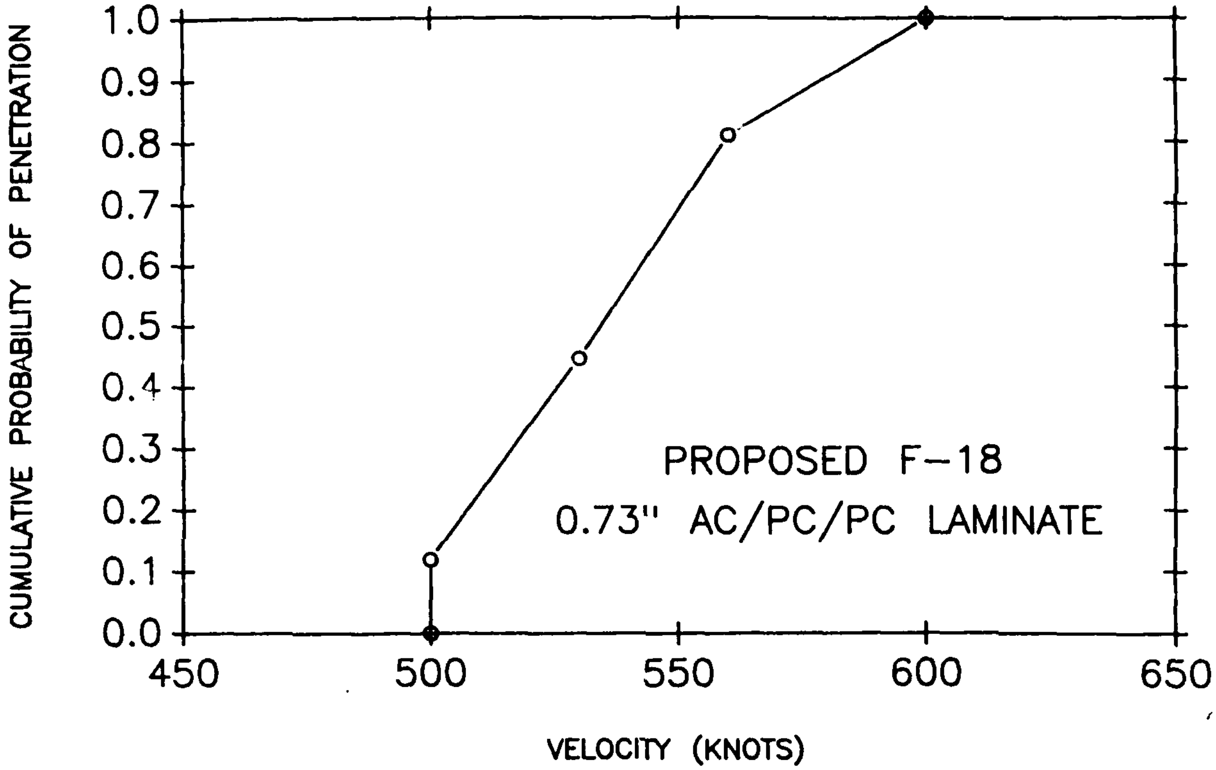


Figure 24. Windshield Strength Distribution Function, Proposed F-18 0.73" AC/PC/PC Laminate.

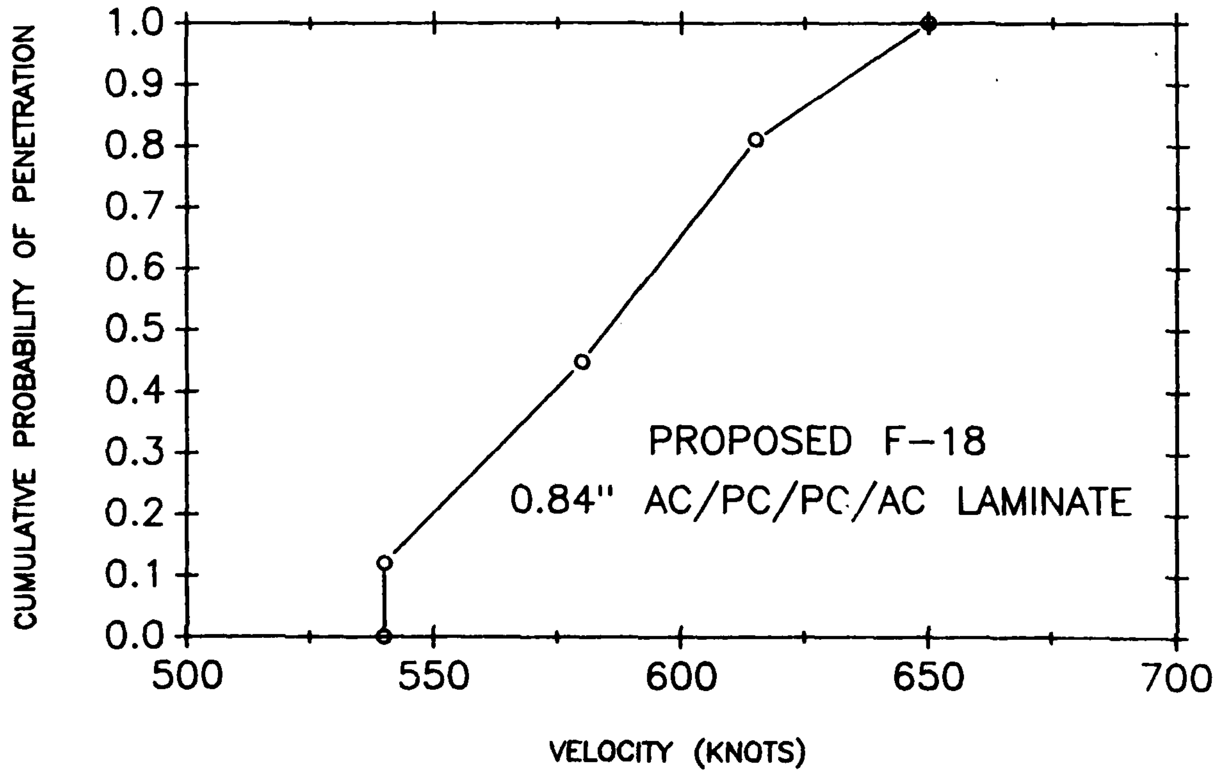


Figure 25. Windshield Strength Distribution Function, Proposed F-18 0.84" AC/PC/PC/AC Laminate.

TABLE 1

SUMMARY OF BIRDSTRIKE RISK ASSESSMENT

Definition of Models	System Capability	Predicted Number of Penetrations in 10 Years	Percent Reduction in Penetrations
Current Windshield System	265	15.8	0
0.6 Coated Polycarbonate	425	5.0	68
0.6 Laminated	450	4.2	73
0.94 Stretched Acrylic	475	3.4	78
0.66 Laminated	475	2.7	83
0.73 Laminated	500	2.3	85
0.84 Laminated	540	1.6	90

system, 15.8 penetrations were predicted in 10 years. The 0.6-inch-thick bird proof polycarbonate transparencies increase the birdstrike resistance capability, lowering the expected penetration by over 60 percent without significantly increasing the weight. The 0.94-inch-thick stretched acrylic transparency has the same minimum capability (475 knots) as the 0.66-inch-thick laminated acrylic/polycarbonate transparency; and results in a total of about three penetrating birdstrikes in a 10-year period.

Two transparency alternatives were evaluated which have greater than 475-knot capability and these may require some fuselage modification to support the impact loads. The transparencies would provide 500 and 540-knot capability and further reduce the number of expected penetrations to about 15% and 10%, respectively, of the current windshield system.

SECTION 7
PRELIMINARY TRANSPARENCY DESIGN/CROSS-SECTION EVALUATION

A method of rating the various transparency design cross sections was devised to systematically evaluate the variables involved in determining the best transparency configurations for further consideration. Nine categories, which included initial cost, life cycle cost, weight, producibility, durability, maintainability, optics, visibility, and birdstrike resistance were evaluated using a matrix evaluation technique. Note that an in-depth evaluation was not performed in each of the above categories; all ratings were relative to each other and not absolute. Seven transparency cross sections were evaluated. These candidate cross sections resulted from transparency configurations that have been used in the past on similar aircraft or that have been suggested as alternate designs by industry.

The transparency evaluation represents the combined rating of UDRI and AFWAL/FDER and were based on their experience gained in past programs. The rating or weighting factors were assigned in each category after considering the explanations listed in the following pages.

- The "design requirement weighting factors" are a rating of the categories relative to each other based on the projected Navy requirements. For example, bird impact was rated higher than weight or cost. The most important category was assigned a "10"; other categories are rated according to the relative importance.
- The "transparency rating" prioritizes each transparency cross section in a given category. The best material is given 10 points. All other cross sections are to be

rated relative to the best, on a scale of 0 to 10. Listed below is an explanation of each category.

- Initial Cost - initial cost of making the retrofit (cost of all hardware and the work required for installation, reflecting any development cost).
- Life Cycle Cost - cost of replacing transparency on an annualized basis.
- Weight - relative weight of the windshield assembly.
- Producibility - rating should reflect the development time required and potential production difficulties (proven vs. new technology).
- Durability - if possible, should be based on the actual service life of similar transparencies.
- Maintainability - any maintenance required on the windshield system.
- Optics - rating reflects expected optics which could be achieved and maintained during production and service.
- Visibility - rates the relative visibility between designs.
- Birdstrike Resistance - rates the relative birdstrike resistance of each design.

o The "Overall Windshield Rating" is the summation of the products for each category of the "Design Requirement Weighting Factor" times the "Transparency Rating."

All transparency designs are a compromise of many different and sometimes conflicting design requirements and goals. This evaluation is an attempt to quantify these requirements and goals in order to objectively select the best alternative. AFWAL/FIER and UDRI conducted this evaluation as objectively as possible based on their combined experience in aircraft transparencies.

The evaluation has been summarized on Table 2. The design requirements weighting factors are summarized in the first line of the table. The transparency rating factors are summarized next, followed by a summary of the overall ratings.

The results of this evaluation are as follows: The 0.6 through 0.73-inch-thick acrylic faced polycarbonate transparencies had the highest overall rating. The 0.94-inch-thick stretched acrylic transparency followed--this design was negatively impacted by weight. The transparency designs with an outer surface coating had the lowest rating.

TABLE 2

OVERALL DESIGN BASED WEIGHTING FACTORS OF WINDSHIELD AND CANOPY

		INITIAL COST	LIFE CYCLE COST	WEIGHT	PRODUCIBILITY	DURABILITY	MAINTAINABILITY	OPTICS	VISIBILITY	BIRDSTRIKE RESISTANCE	TOTAL
	Design Requirement Weighting Factors	6	8	9	7	7	7	9	9	10.0	
TRANSPARENCY RATING	.6 Coat	10	6	10	7	6	7	9	10	5	
	.6 Coat Laminate	10	6	10	10	6	7	8	10	6	
	.6 Acrylic Laminate	10	8	10	10	8	10	8	10	6	
	.94 SA	9	10	4	6	10	10	10	8	7	
	.66 Acrylic Laminate	10	8	9	10	8	10	8	10	7	
	.73 Acrylic Laminate	8	8	8	10	8	10	8	9	8	
	.84 Acrylic Laminate	4	7	6	10	8	10	7	8	10	
	.6 Coat	60	48	90	49	42	49	81	90	50	559
	.6 Coat Laminate	60	48	90	70	42	49	72	90	60	581
	.6 Acrylic Laminate	60	64	90	70	56	70	72	90	60	632
	.94 SA	54	80	36	42	70	70	90	72	70	594
	.66 Acrylic Laminate	60	64	81	70	56	70	72	90	70	633
	.73 Acrylic Laminate	48	64	72	70	56	70	72	81	80	613
	.84 Acrylic Laminate	24	56	54	70	56	70	63	72	100	565

Overall Windshield Rating Factor = Transparency Rating x Design Requirement Rating Factor

SECTION 8
BASELINE BIRDSTRIKE TEST RESULTS

Baseline birdstrike tests were conducted at Arnold Engineering Development Center (AEDC), Arnold Air Force Station, Tullahoma, TN, during August 1987. The results of these tests are contained in Reference 18. Figure 26 shows the two impacted points on the transparency. Table 3 presents a summary of the birdstrike test results. All tests were conducted using a 4-pound bird. Two impacts were made at the critical location (along the aircraft centerline just forward of the aft arch), a 225-knot pass and a 269-knot failure. Four birdstrike tests were conducted on the center of the windshield resulting in a pass at 309 knots and a failure at 330 knots.

Twenty-one strain measurements were made on each shot for shot numbers 975 through 978 and 980. Figures 27 and 28 show the strain gage locations, and cross section properties.

The strain data from test no. 975 was used to validate the windshield support structure analysis contained in Appendix A. This was the only shot on impact point 1 (the most critical location) which passed--loads in the aft arch would be lower for shots at other locations, and strain data from a shot which fails cannot be used for validation calculations because the amount of energy absorbed in the system would be unknown. The strain gages on the aft arch showed the arch began to yield during this 225 knot test.

The strain data for three points on rib 240.2 are shown in Figure 29. Peak strains occurred at about 1.74 milliseconds into the impact event. Using the stress equation shown in Figure 30, a static load on the rib was calculated which would result in the measured strain (averaged strains were used from the left and right sides).

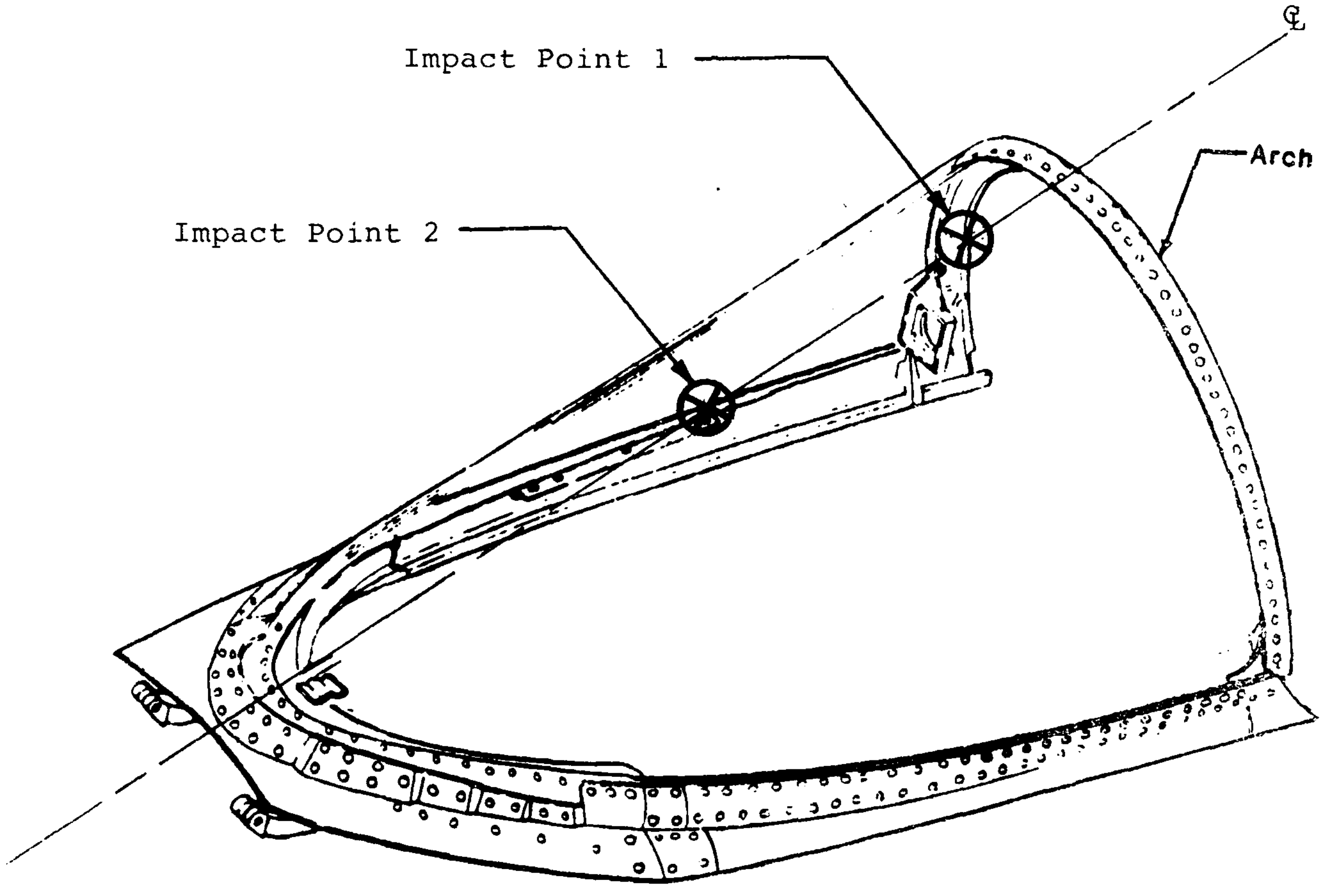


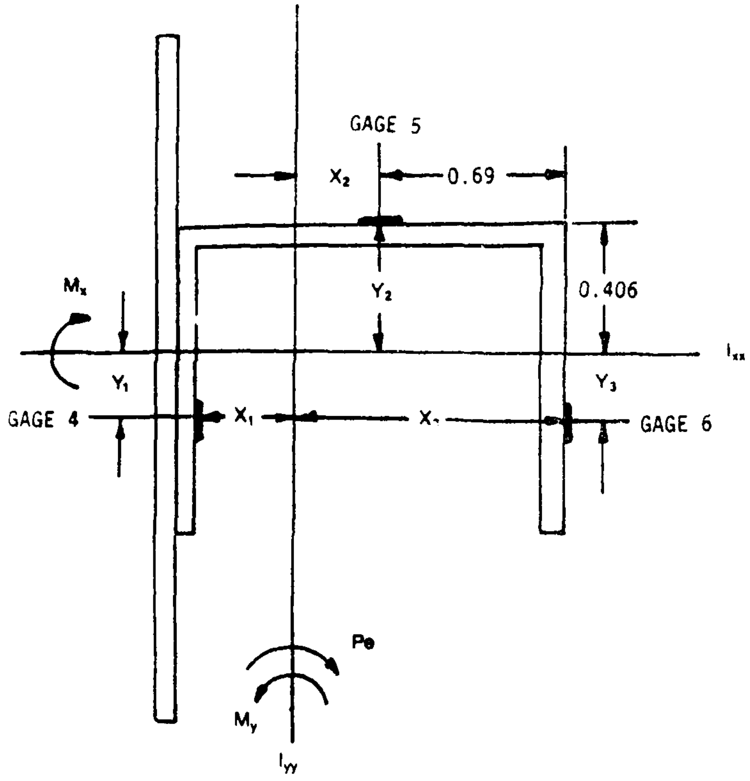
Figure 26. Bird Impact Test Points.

TABLE 3

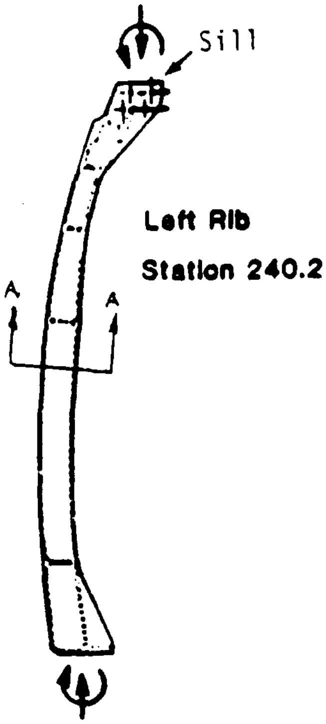
SUMMARY OF BIRDSTRIKE TEST RESULTS

Transparency No.	Shot No.	Date	Transparency Temp (°F)	Velocity (knots)		Bird Weight (lb)	Impact Point	Results
				Desired	Actual			
1	975	8-10-87	85	225	225	4	1	Passed
1	976	8-11-87	82	245	250	4	2	Passed
1	977	8-11-87	88	340	346	4	2	Failed
2	978	8-13-87	81	265	269	4	1	Failed
4	980	8-17-87	89	305	309	4	2	Passed
5	981①	8-20-87	91	330	330	4	2	Failed

① Strain gages were not included in the instrumentation.



Section A-A



GAGE TYPE: CEA-13-125UW-350

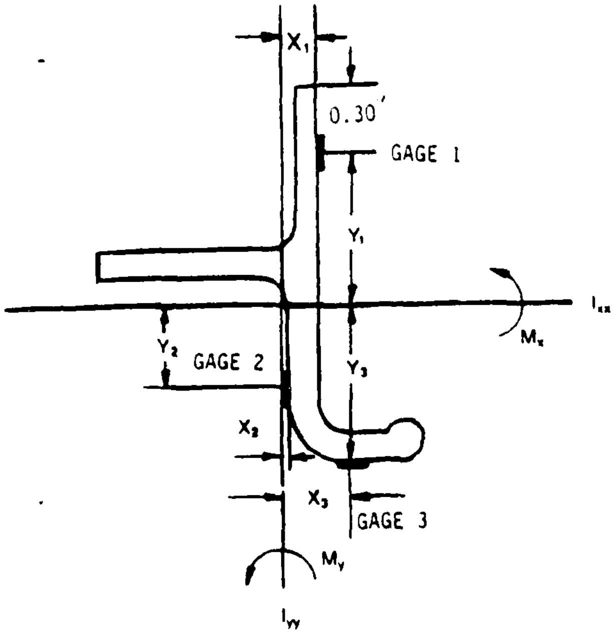
Section A-A Strain Gage Locations

	Gage 1	Gage 2	Gage 3
Right Rib	13.9"	13.9"	13.9"
	Gage 4	Gage 5	Gage 6
Left Rib	13.87"	14.25"	14.0"

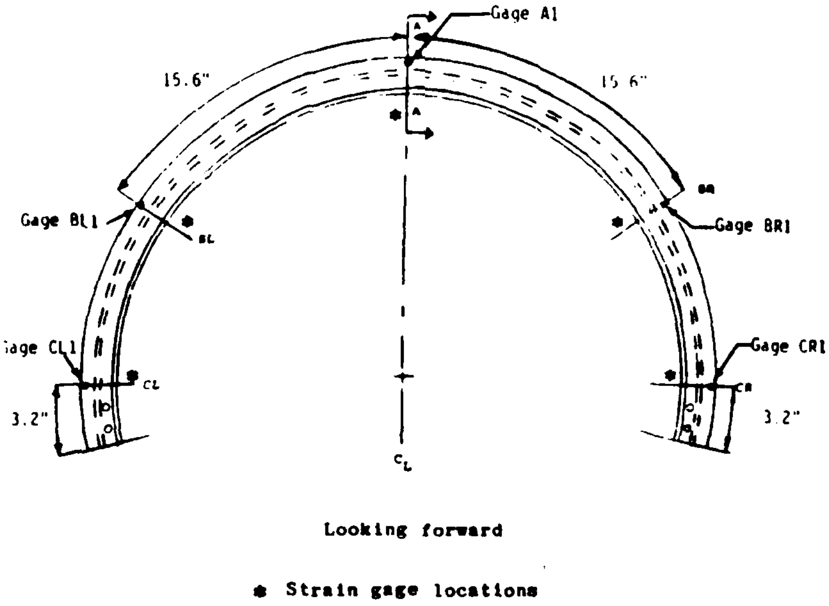
RIB SECTION PROPERTIES

X_1 = -0.39 in.	Y_1 = 0.19 in.	I_X = 0.086 in^4	e = -3.36 in.
X_2 = 0.22 in.	Y_2 = 0.40 in.	I_Y = 0.111 in^4	A = .366 in^2
X_3 = 0.91 in.	Y_3 = 0.19 in.	E = 10.6×10^6 psi	

Figure 27. Summary of Strain Gage Locations and Cross Section Properties on Rib Y240.2.



Section A-A



GAGE TYPE: CEA-13-125UW-350

ARCH SECTION PROPERTIES

X_1 = 0.14 in.	Y_1 = -0.69 in.	I_X = 0.07 in^4	E = $10.6x10^6$ psi
X_2 = 0.01 in.	Y_2 = 0.31 in.	I_Y = 0.04 in^4	e = 0. in.
X_3 = 0.31 in.	Y_3 = 0.71 in.	A = 0.37 in^2	

Figure 28. Summary of Strain Gage Locations and Cross Section Properties for Windshield Aft Arch.

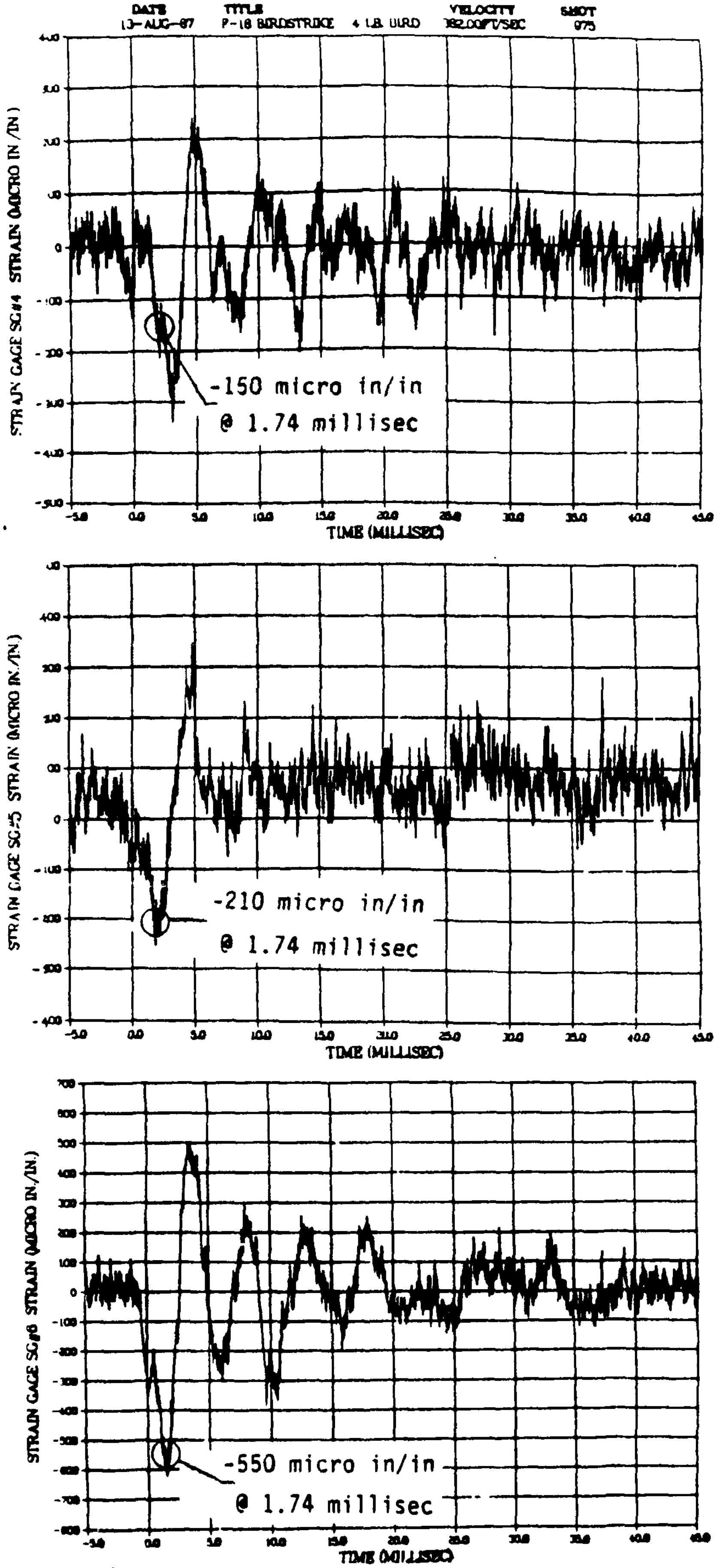


Figure 29. Strain Gage Data on Left Rib at Station Y240.2 for Shot 975.

$$\sigma_1 = \varepsilon_1 E = \frac{M_X Y_1}{I_X} + \frac{M_Y X_1}{I_Y} + \frac{PeX_1}{I_Y} - \frac{P}{A}$$

$$\sigma_2 = \varepsilon_2 E = \frac{M_X Y_2}{I_X} + \frac{M_Y X_2}{I_Y} + \frac{PeX_2}{I_Y} - \frac{P}{A}$$

$$\sigma_3 = \varepsilon_3 E = \frac{M_X Y_3}{I_X} + \frac{M_Y X_2}{I_Y} + \frac{PeX_2}{I_Y} - \frac{P}{A}$$

Where: M_X = Bending moment about the x-axis.

M_Y = Bending moment about the y-axis.

P = Axial load.

A = Cross-sectional area.

E = Modulus of elasticity.

e = Eccentricity of the axial load.

I_X = Moment of inertia about the x-axis.

I_Y = Moment of inertia about the y-axis.

X_i = Distance measured from gage i to the neutral x-axis.

Y_i = Distance measured from gage i to the neutral y-axis.

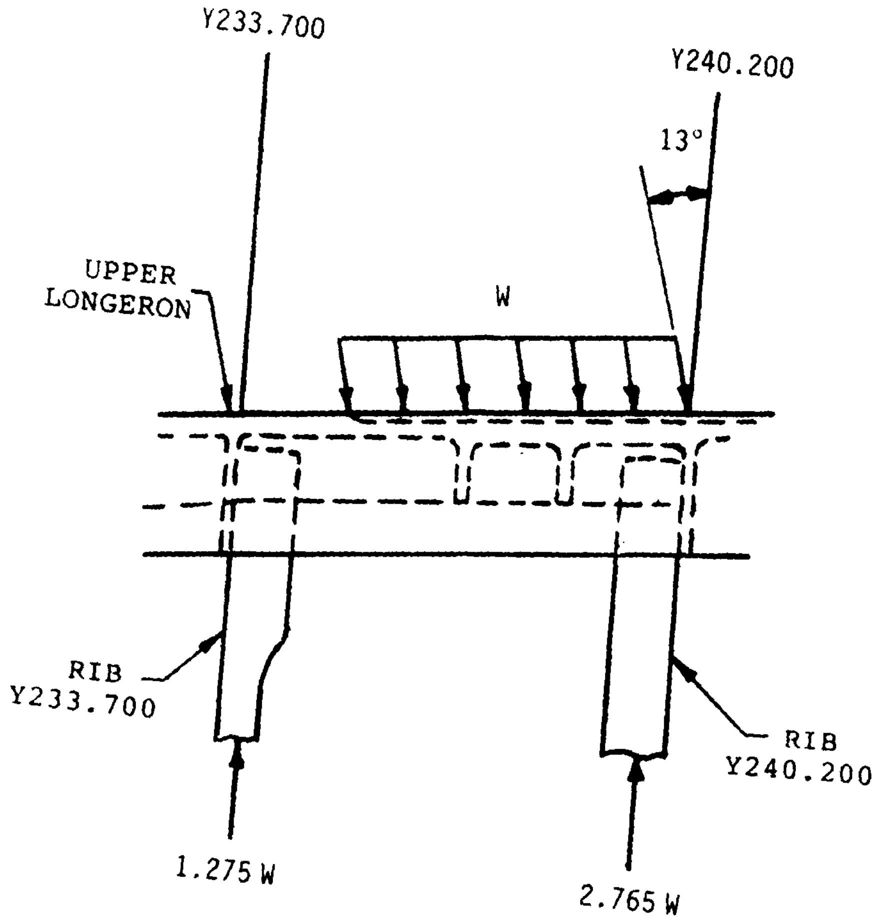
σ_i = Stress calculated in gage i.

ε_i = Strain measured in gage i.

Figure 30. Stress Equations for Reducing Strain Data. (Reference 19)

The average peak load on the rib at station Y240.2 was 1170 lbs. downward force with an outward moment of 380 ft. lbs. The actual load in the arch at the sill was then calculated as shown in Figure 31. This resulted in an applied down force from the arch to the sill, of 1680 lbs. The compares favorably with the estimated load (1590 lbs.) predicted from Figure 9.

As a result of these birdstrike tests and structural analysis (Appendix A) it was estimated that some fuselage damage could occur in the 450 to 470-knot velocity range. Damage to the fuselage in this area as a result of birdstrike would not be expected to prevent the aircraft from returning home, based on discussions with NAVAIR concerning the location of critical flight control components.



$P = 2.765\,W \qquad P_S = \dfrac{3.99\,W}{\cos 13^\circ}$

Where: P = Axial loading in rib Y240.200

P_S = Birdstrike arch load on sill

W = Distributed arch load on sill

Figure 31. Calculation of Load at Sill.

SECTION 9
CONCLUSIONS

The windshield system alternatives have been summarized in Table 4 along with information in eight key areas. These areas include birdstrike capability, predicted number of penetrations, weight change, optics, peak deflection at design capability, technical risk, durability and life cycle cost.

The following paragraphs summarize the various windshield alternatives and present the trade-offs that each represents.

- The 0.6-inch-thick coated monolithic polycarbonate transparency would provide a capability of 425 knots, reducing the number of penetrating strikes from 15.8 to 5 in a 10-year period. There is no weight change for this alternative (a new aft windshield arch could add several pounds). All of the existing windshield frame could be used except for the aft arch, which would have to be redesigned. Optics would be slightly degraded from the current system (a result of the coating) and peak deflection from birdstrikes would be about 4.5 inches. Technical risk is high because new coating systems which provide adequate durability have yet to be proven in production.

- The 0.6-inch-thick coated laminated polycarbonate transparency is very similar to the monolithic transparency. However, the laminated transparencies facilitate the incorporation of electrically conductive coatings for deicing and threat suppression. There is a reduction in optics due to laminating the material. The bird impact resistance would be about 450 knots--again, the coatings represent a higher technical risk.

TABLE 4

SUMMARY OF WINDSHIELD SYSTEM ALTERNATIVES

DESCRIPTION	MINIMUM CAPABILITY (KNOTS)	PENETRATIONS IN 10 YEARS	WEIGHT CHANGE (POUNDS)	OPTICS (MINUTES OF ARC)	PEAK DEFLECTION AT DESIGN CAPABILITY (INCHES)	TECHNICAL RISK	DURABILITY (YEARS)	LIFE CYCLE COST ($K/10 YEARS)	OVERALL RATING
0.6" COATED MONOLITHIC POLY	425	5.0	N.C.	2	4.5	HIGH	2-5	12-14	7
0.6" COATED LAMINATED PC/PC	450	4.2	N.C.	5	5.0	HIGH	2-5	14-16	5
0.6" LAMINATED AC/PC/PC	450	4.2	N.C.	5	4.25	LOW	3-6	11-13	2
0.94" STRETCHED ACRYLIC	475**	3.4	+26.4	1**	1.0	HIGH	4-7	8-10	4
0.66" LAMINATED AC/PC/PC	475	2.7	+5.0	5	4.25	LOW	3-6	11-13	1
0.73" LAMINATED AC/PC/PC	500*	2.3	+12.0	5	4.0	LOW	3-6	11-13	3
0.84" LAMINATED AC/PC/PC/AC	540*	1.6	+19.0	5	3.75	LOW	3-6	11-13	6
COMPOSITE ARCH	475		+6.5		2.5	MED	LIFE OF AC	4-6	
TITANIUM ARCH	475		+3.9		2.5	LOW	LIFE OF AC	4-6	
REINFORCED ALUM. ARCH	475		+5.5		2.5	MED	LIFE OF AC	4-6	
ALUMINUM ARCH FOR .94 ACRYLIC	475		+3.5		0.8	LOW	LIFE OF AC	1-2	

NOTE: 15.8 PENETRATIONS IN 10 YEARS WITH THE CURRENT SYSTEM
CURRENT WINDSHIELD WEIGHT: 46.61 LBS
CURRENT ARCH WEIGH: 1.82 LBS

* REQUIRES FUSELAGE MODIFICATIONS
**REQUIRES R&D

- The 0.6-inch-thick acrylic faced laminated polycarbonate transparency is similar to the other two 0.6-inch-thick transparencies; however, this type of cross section design has been proven to have adequate durability on a production basis on other aircraft and represents a low technical risk. Optics would not be as good as monolithic designs; however, they should be adequate to meet mission requirements.

- The 0.94-inch-thick monolithic stretched acrylic transparency could provide up to 475-knot capability, but may require a substantial development program making it a high technical risk. When developed, peak deflection would be only about an inch reducing the possibility of damage to the HUD. The potential exists for catastrophic failure of this transparency system when impacted at velocities slightly higher than the threshold velocity. It provides good optics and durability; however, the weight of the windshield would increase by 26.4 pounds. This transparency would require an all-new, completely redesigned frame.

- The 0.66-inch-thick acrylic-faced laminated polycarbonate transparency is essentially the same as the 0.6-inch-thick acrylic-faced laminate. The difference is a slightly higher bird impact resistance at a slightly increased weight (about 5 pounds). This transparency has the same minimum capability (475 knots) as the 0.94-inch stretched acrylic windshield, and represents a low technical risk.

- The 0.73-inch-thick acrylic-faced laminated polycarbonate transparency is the same cross-section that has been used on the USAF F-111 aircraft for the past 8 years. This alternative would provide 500

knot birdstrike protection (may require some fuselage modification) and would weigh 12 pounds more than the current transparency. Also, the entire windshield frame would have to be redesigned because of the additional transparency thickness.

- The 0.84-inch-thick acrylic-faced laminated polycarbonate transparency would provide 540-knot birdstrike protection (may require fuselage modification) and reduce the predicted number of penetrations by 90%. This cross-section alternative is similar to the 0.73-inch-thick transparency except it has acrylic face plies on both the inside and outside surfaces and would result in a weight increase of 19 pounds over the current system.

Four aft windshield arch design concepts (see Figure 32) were evaluated. Each arch was designed to support a transparency having a 4-pound, 475-knot-birdstrike resistance capability. The aft arch is the most critical (in terms of the bird impact performance) to the overall performance of the windshield system. The composite, titanium, and reinforced aluminum arch designs can be used with all of the transparency alternatives except the 0.94-inch-thick monolithic acrylic, which would use an aluminum design.

- An all-composite (glass/Kevlar/epoxy) aft arch has yet to be demonstrated in service but has the advantage (over a metal arch) of rebounding back into its original shape after being bird impacted.

- A titanium aft arch has been used on the USAF F-111 BIRT and ADBIRT windshield systems. This type of arch may plastically deform leaving an air gap between the windshield and canopy. This design, however, may have

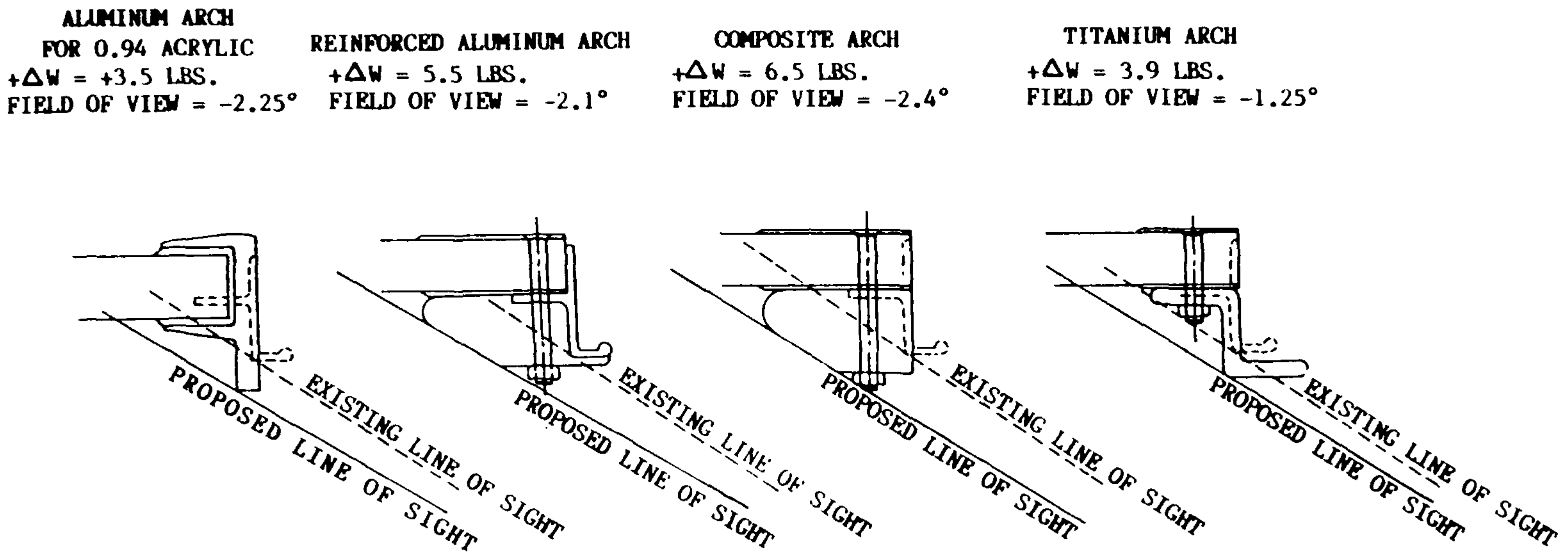


Figure 32. Proposed Arch Designs.

the lightest weight and provide the greatest visibility.

- o A composite reinforced aluminum arch would be similar to what has been developed for the USAF T-38 aircraft. This design provides a compromise between the all-metal and all-composite arch designs. A prototype design for the T-38 is being flight tested; however, there is no long-term in-service history. The advantage of this design is that on a retrofit, the original arch is reinforced and incorporated into the new windshield system, minimizing the amount of new structure that has to be designed and requalified.

- o The aluminum frame design for the 0.94-inch-thick transparency was conceived by the McDonnell Aircraft Company. As shown in Figure 32, the visibility would be degraded compared with the titanium arch. This arch would have to be developed to provide support to the transparency without degrading the system impact performance. The adhesive/sealant used between the transparency and arch would be critical to the overall system performance.

SECTION 10
RECOMMENDATIONS

The following recommendation, summarized on Figure 33, was presented as a result of this study.

The existing 0.6-inch-thick monolithic stretched acrylic windshield should be replaced to reduce the risk of penetrating birdstrike. A 0.66-inch-thick laminated acrylic/polycarbonate transparency is recommended because it significantly reduces the birdstrike hazard (by over 80%). Similar transparency designs have been used on USAF high-performance fighter aircraft (F-16, F-111, T-38, and F-4), resulting in a low technical risk. Also, laminated designs facilitate the incorporation of coatings for deicing and threat suppression.

The 0.66-inch-thick laminated acrylic/polycarbonate transparency was selected for three reasons. First, it would provide a level of protection that would minimize the possibility of damage to the fuselage while significantly reducing the birdstrike hazard. Second, initial cost and development time would be minimized by using the existing windshield frame (except for the aft arch). Third, weight increase over the current system would be minimized (about a 10% increase).

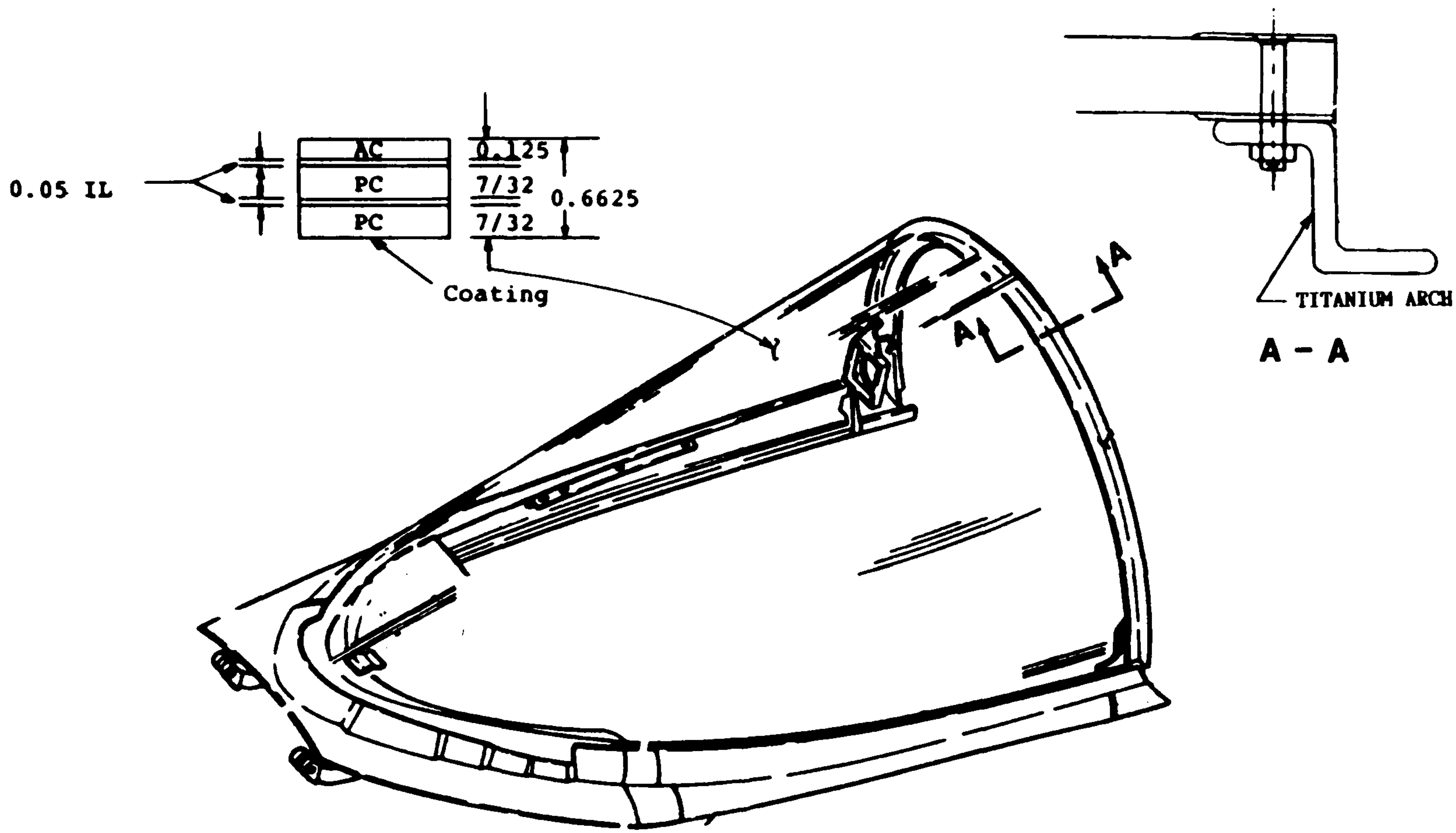


Figure 33. Recommended F-18 Transparency System.

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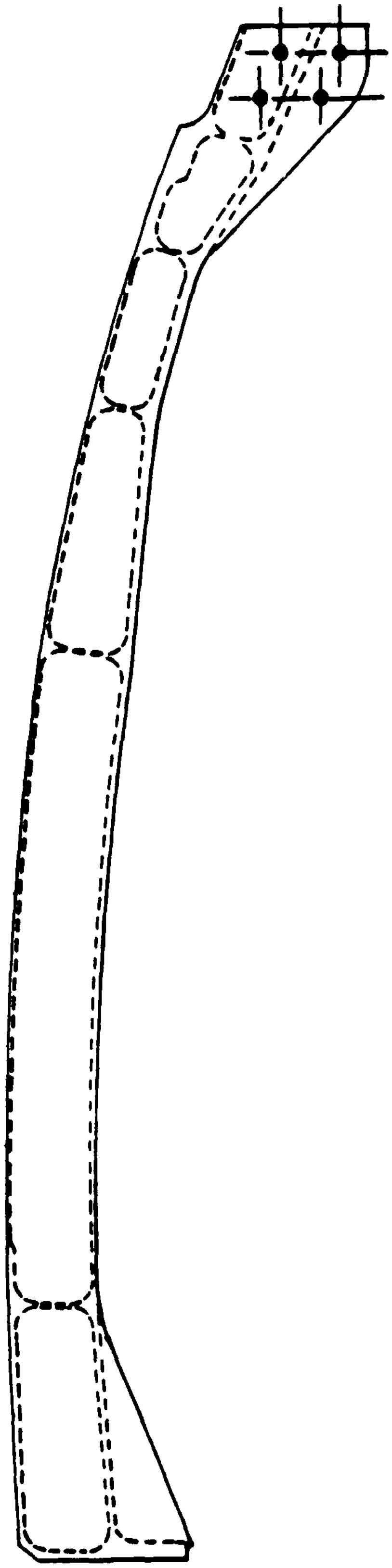
APPENDIX A

STRUCTURAL ANALYSIS OF CRITICAL WINDSHIELD SYSTEM SUPPORT STRUCTURE

TABLE OF CONTENTS

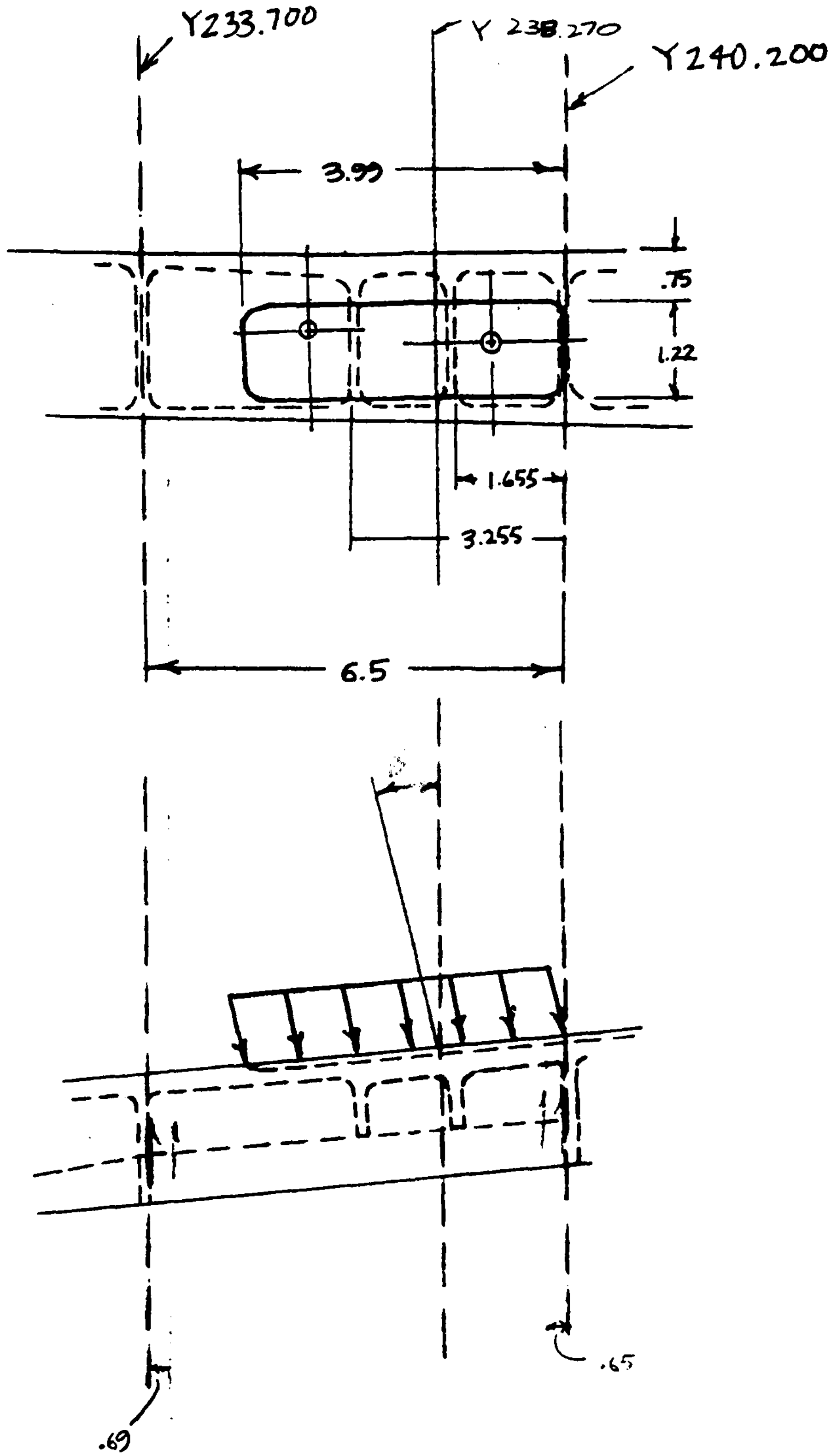


1. Column is assumed to take the shape of a circular arc.
2. Column is assumed to have either a fixed-pinned end condition or a pinned-pinned end condition.
3. Skin covering column is assumed to have simply supported ends, one simply supported side, and one free side.
4. Arch applies a distributed moment to the column upon birdstrike. This moment will increase the birdstrike load.

CRITICAL FAILURE POINTS

crippling failure:	P_{max} = 5540 lbs	(pinned-pinned)
	P_{max} = 5690 lbs	(fixed-pinned)
buckling failure:	P_{max} = 9200 lbs	(pinned-pinned)
	P_{max} = 9752 lbs	(fixed-pinned)
bearing load failure:	P_{max} = 7020 lbs	

NOTE: P_{max} = the maximum allowable birdstrike load

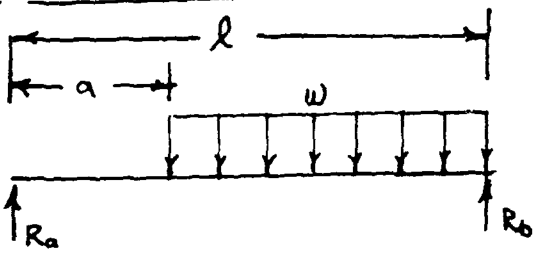


Y233.700
Y 238.270
Y240.200
3.99
.75
1.22
1.655
3.255
6.5
.65
.69

FAILURE ANALYSIS OF UPPER LONGERON

BENDING STRESS ANALYSIS — LONGERON

(NOTE EQUATIONS TAKEN FROM PG 1[illegible] OF FORMULAS FOR STRESS AND STRAIN)



ω = LOAD PER UNIT LENGTH

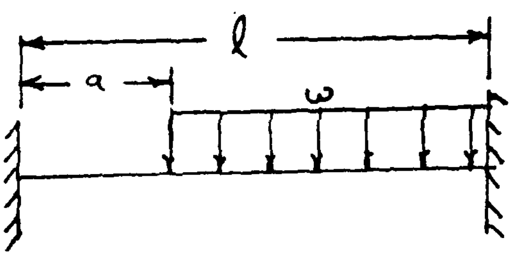
$l = 6.5$ in
$a = 6.5 - 3.99 = 2.51$ in

I. FOR PINNED/PINNED CONDITION — DIAGRAM ABOVE

$$\left\{ \begin{aligned} R_a &= \frac{\omega}{2l}(l-a)^2 \\ R_b &= \frac{\omega+\omega}{2}(l-a) - R_A = \omega(l-a) - \frac{\omega}{2l}(l-a)^2 \end{aligned} \right\}$$

II. FOR FIXED/FIXED CONDITION

$$\left\{ \begin{aligned} R_A &= \frac{\omega}{2l^3}(l-a)^3(l+a) & \quad R_B &= \frac{\omega+\omega}{2}(l-a) - R_A = \omega(l-a) - R_A \\ M_A &= \frac{-\omega}{12l^2}(l-a)^3(l+3a) & \quad M_B &= R_A l + M_A - \frac{\omega}{2}(l-a)^2 \end{aligned} \right\}$$

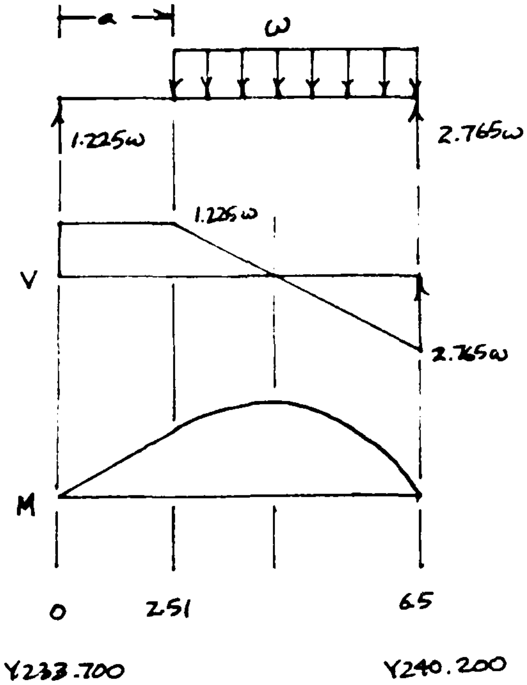


$l = 6.50 - .65 - .69 = 5.16$ in
$a = 2.51 - .69 = 1.82$ in

ASSUMPTIONS

1. LOAD IS EVENLY DISTRIBUTED ALONG THE SUPPORT WINDSHIELD ATTACH.
2. LOAD AT ANY CROSS-SECTION IS DISTRIBUTED THROUGH THE CENTROID
3. THE PINNED/PINNED CONDITION WILL BE ANALYZED SINCE IT IS MORE LIKELY TO FAIL BEFORE THE FIXED/FIXED CONDITION

I. FOR PINNED/PINNED CONDITION



V FROM 0 to 2.51 : $V = 1.225\,\omega$

V FROM 2.51 to 6.5 : $V = 1.225\omega - \int_{2.51}^{6.5} \omega\,dx$

M FROM 0 to 2.51 : $M = \int V dx = \int_0^{2.51} 1.225\omega\,dx$

M FROM 2.51 to 6.5 : $M = \int_0^{2.51} 1.225\omega\,dx + \int_{2.51}^{6.5} (b - \omega x)\,dx$

WHERE b IS THE INTERCEPT OF THE LINE ON THE V-AXIS. IT IS FOUND AS FOLLOWS

AT $x = 6.5$, $V = -2.765\omega$

THEREFORE
$$V = -\omega x + b$$
$$-2.765\omega = b - 6.5\omega$$
$$b = 3.735\,\omega$$

M FROM 2.51 to 6.5 : $M = \int_0^{2.51} 1.225\omega + \int_{2.51}^{6.5} \omega(3.735 - x)\,dx$

$$M = 3.075\omega + \int_{2.51}^{6.5} \omega(3.735 - x)\,dx$$

THE ABOVE EQUATIONS WILL BE USED TO FIND THE POSITION ON THE LONGERON WHICH WILL FAIL UNDER THE APPLIED STRESS.

(*) THE LONGERON WILL BE ANALYZED FOR THE CASE OF UNSYMMETRICAL BENDING.

THE LONGERON WILL BE ANALYZED AT TWO CRITICAL POSITIONS

(1) AT Y 236.940 → CROSS-SECTION HAS THE LEAST LOAD CARRYING CAPACITY

(2) AT Y237.440 → CROSS-SECTION CARRIES THE MAXIMUM BENDING MOMENT.

THE ANALYSIS WILL ALSO INCLUDE THE SHEAR STRESS CAUSED BY THE MOMENT PRODUCE IN THE ARCH WHEN BIRDSTRIKE OCCURS.

(1) AT Y236.940 — LEAST LOAD CARRYING CAPACITY

TO DO THE UNSYMMETRICAL BENDING ANALYSIS, DISTANCES a, b, c, d, AND e MUST BE DETERMINED. (SEE FIGURE 1)

DISTANCE a $\quad \tan 12.4^\circ = \frac{a}{1.66}$

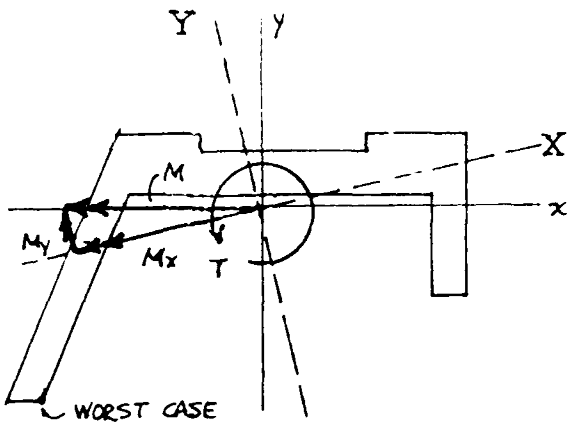
$$a = 1.66 \tan 12.4^\circ = .37 \text{ in}$$

DISTANCE b: $\quad b = \frac{1.66}{\cos 12.4^\circ} = 1.70 \text{ in}$

DISTANCE d: $\quad d = 1.46 - a = 1.46 - .37 = 1.10 \text{ in}$

DISTANCE c: $\quad c = d \cos 12.4^\circ = 1.10 \cos 12.4 = 1.07 \text{ in}$

DISTANCE e: $\quad e = d \sin 12.4^\circ = 1.10 \sin 12.4^\circ = .24 \text{ in}$



MOMENTS AROUND PRINCIPAL AXES

$$M_x = M \cos 12.4^\circ$$

$$M_y = M \sin 12.4^\circ$$

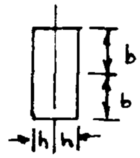
$$\sigma = \frac{M_x c}{I_x} + \frac{M_y (b+e)}{I_y}$$

$$\tau = \frac{2Th}{J}$$

THE TORSION T IS ACTUALLY THE MOMENT PRODUCED IN THE ARCH WHEN BIRDSTRIKE OCCURS. A MOMENT OR TORQUE OF 500 ft-lb WILL BE ASSUMED. NOTE THAT THIS NUMBER IS BELOW THE MAXIMUM ALLOWABLE MOMENT CALCULATED IN SECTION 5.0.2.

T = TORQUE = 500 ft·lb

J = TORSIONAL RIGIDITY FACTOR $= C \frac{1}{3} \sum_{i=1}^{n} (2b_i)(2h_i)^3$



$C = .91$ FOR SECTIONS WHERE $b_i < 10h_i$

$C = 1.0$ FOR SECTIONS WHERE $b_i > 10h_i$

h = THICKNESS OF REGION BEING ANALYZED

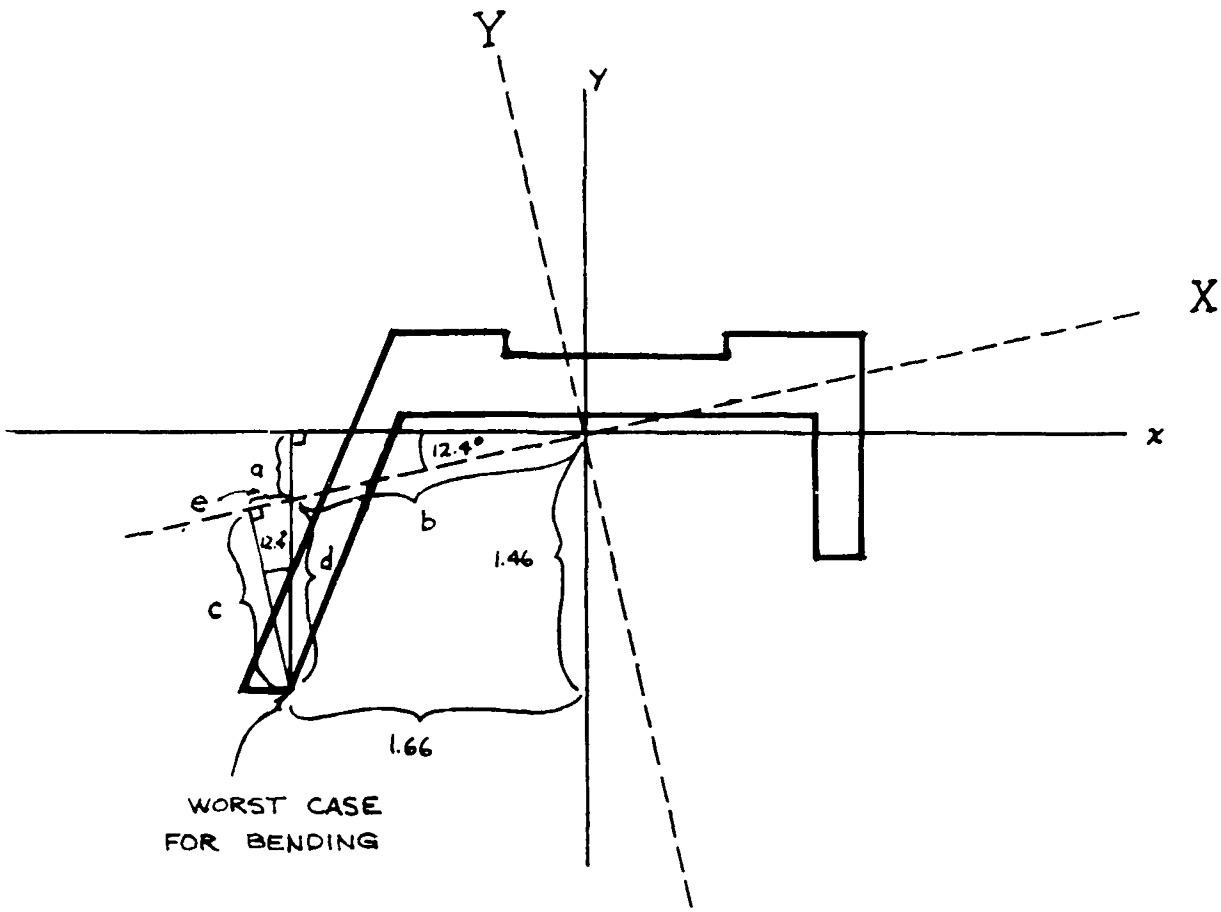


FIGURE 1 - CROSS-SECTION AT Y236.940

1	0.00000	0.00000	7	3.45000	2.00000
2	.84000	2.00000	8	3.45000	.75000
3	1.48000	2.00000	9	3.30000	.75000
4	1.48000	1.87500	10	3.20000	1.55000
5	2.70000	1.87500	11	.84000	1.55000
6	2.70000	2.00000	12	.24000	0.00000

Y DISTANCE TO XX CENTROIDAL AXIS = 1.4646

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .3707

X DISTANCE TO YY CENTROIDAL AXIS = 1.7026

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS 1.7137

TOTAL AREA = 1.[illegible]70

PRODUCT OF INERTIA = .3559

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = 1.7918

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .2926

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = 12.4 DEGREES

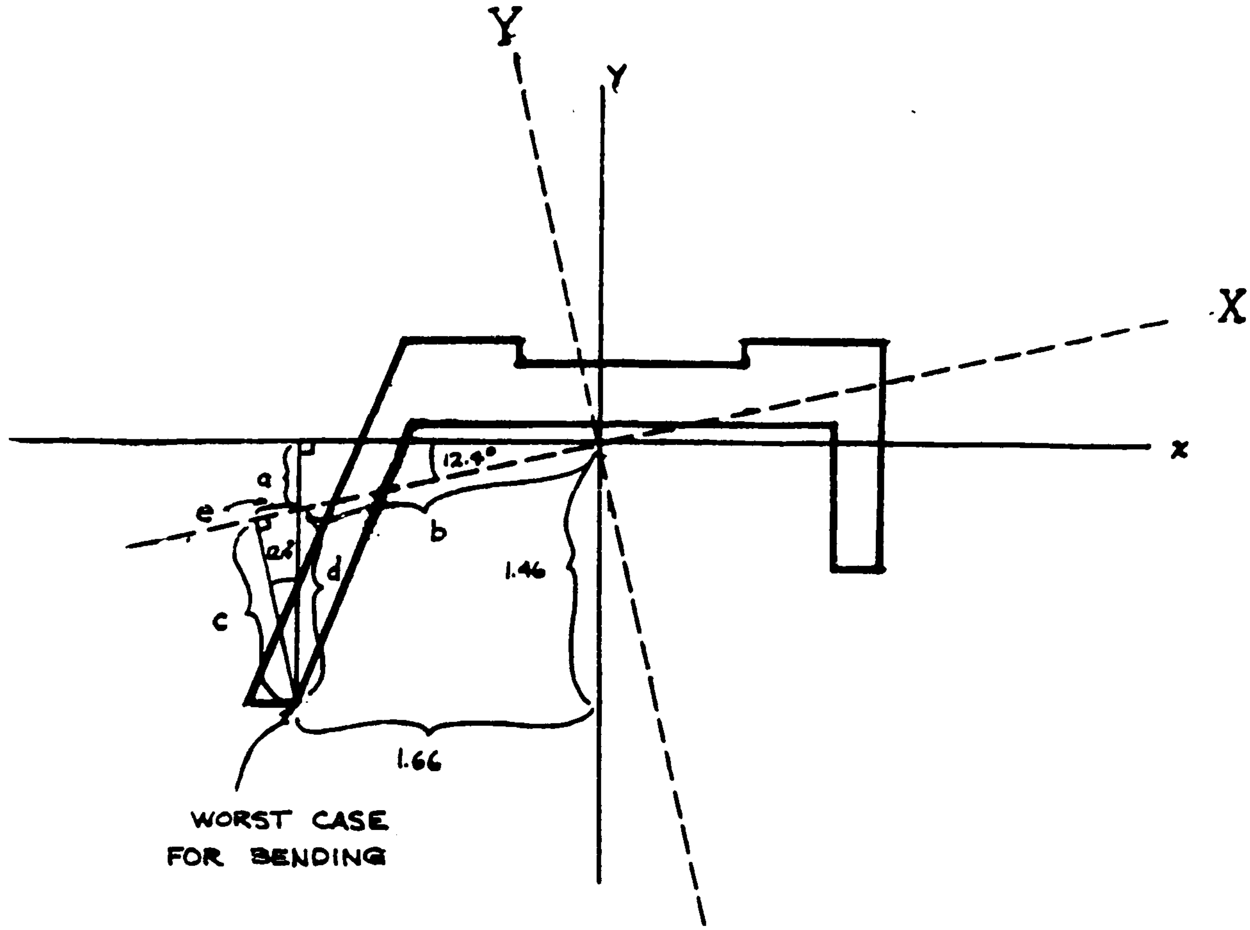


FIGURE 1 - CROSS-SECTION AT Y236.940

1	0.00000	0.00000	7	3.45000	2.00000
2	.84000	2.00000	8	3.45000	.75000
3	1.48000	2.00000	9	3.20000	.75000
4	1.48000	1.87500	10	3.20000	1.55000
5	2.70000	1.87500	11	.84000	1.55000
6	2.70000	2.00000	12	.24000	0.00000

Y DISTANCE TO XX CENTROIDAL AXIS = 1.4646

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .3707

X DISTANCE TO YY CENTROIDAL AXIS = 1.9026

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS = 1.9137

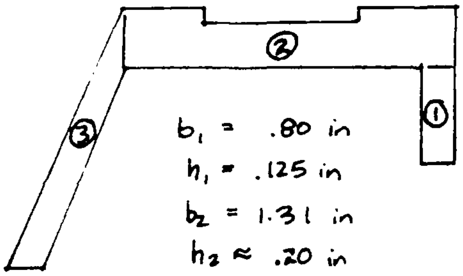
TOTAL AREA = 1.5970

PRODUCT OF INERTIA = .3559

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = 1.9918

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .2926

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = 12.4 DEGREES



$b_1 = .80$ in
$h_1 = .125$ in
$b_2 = 1.31$ in
$h_2 \approx .20$ in
$b_3 \approx 1.0$ in
$h_3 \approx .12$ in

$$J = (\tfrac{1}{3})(.91)\left[(1.6)(.26)^3 + (2.61)(.4)^3 + (20)(.24)^3\right]$$
$$J = .0666 \text{ in}^4$$

AT WORST CASE: $h = \frac{1}{2}t = (\frac{1}{2})(.24) = .12$ in

$$\tau = \frac{2Th}{J} = \frac{(2)(6000 \text{ in·lb})(.12)}{.0666}$$
$$\tau = 21621 \text{ psi}$$

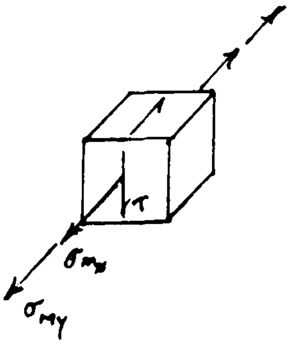
FOR BENDING STRESS:
(NOTE: IN TENSION

$$\sigma = \frac{(M\cos 12.4°)(1.07)}{1.992} + \frac{(M\sin 12.4°)(1.10 + .24)}{.2926}$$

$$M = \frac{\sigma}{\frac{(\cos 12.4)(1.07)}{1.992} + \frac{(\sin 12.4)(1.34)}{.2926}}$$

$$M = .6631\,\sigma \text{ lb·in}$$

TO FIND MAXIMUM ALLOWABLE MOMENT, THE PRINCIPLE STRESS MUST BE FOUND USING "MOHR'S CIRCLE" EQUATIONS



$$\sigma_{max} = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \sqrt{\frac{1}{4}(\sigma_{xx} - \sigma_{yy})^2 + \tau^2}$$

$\sigma_{max} = F_{ty} = 57000$ psi (MATERIAL 7075-T7351)
$\sigma_{yy} = 0$
$\tau = 21621$ psi

$$57000 = \frac{\sigma_{xx}}{2} + \sqrt{(\tfrac{1}{4})(\sigma_{xx})^2 + (21621)^2}$$

$$\left(57000 - \frac{\sigma_{xx}}{2}\right)^2 = \frac{1}{4}(\sigma_{xx})^2 + (21621)^2$$

$$(57000)^2 - (2)(57000)\left(\frac{\sigma_{xx}}{2}\right) + \frac{\sigma_{xx}^2}{4} = \frac{1}{4}\sigma_{xx}^2 + (21621)^2$$

$$\sigma_{xx} = \frac{(57000)^2 - (21621)^2}{57000}$$

$$\sigma_{xx} = 48800 \text{ psi}$$

MAXIMUM MOMENT TO FAIL LONGERON

$$M_{max} = .6631\,\sigma_{xx} = (.6631)(48800) = 32358 \text{ lb·in}$$

MOMENT AT Y 236.940 :

$$M = 3.075\,\omega + \int_{2.51}^{3.24} \omega\,(3.735 - x)\,dx$$

$$M = 3.075\omega + \omega\left(3.735x - \tfrac{1}{2}x^2\right)\Big|_{2.51}^{3.24}$$

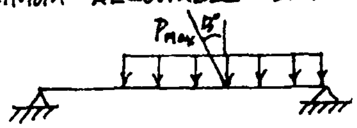
$$M = 3.703\,\omega$$

ALLOWABLE FORCE PER UN. LENGTH
AT Y 236.94

$$M = 3.703\,\omega$$

$$\omega = \frac{M_{max}}{3.703} = \frac{32358}{3.703} = 8739\ \frac{lb}{in}$$

MAXIMOM ALLOWABLE BIRDSTRIKE



$$P_{max} = \frac{3.99\,\omega}{\cos 13^\circ} = \underline{\underline{35785\ lb}}$$

(2) AT SECTION Y 237.440 - MAXIMUM MOMENT POSITION

THIS WILL BE ANALYZED THE SAME WAY AS SECTION Y236.940

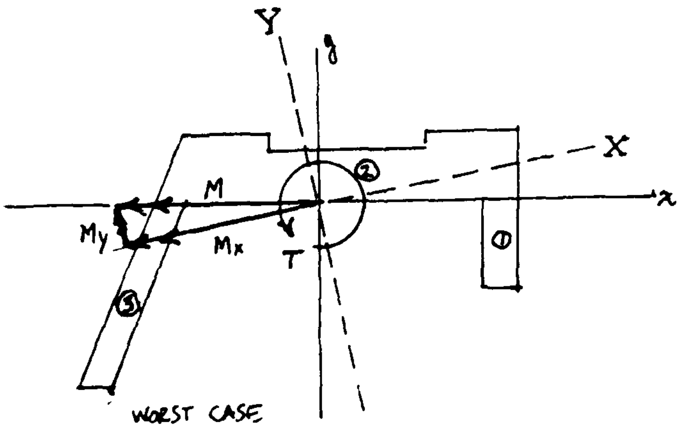
DISTANCE a : $a = 1.66 \tan 11.5^\circ = .34$ in

DISTANCE b : $b = 1.66 / \cos 11.5^\circ = 1.69$ in

DISTANCE d : $d = 1.45 - a = 1.45 - .34 = 1.11$ in

DISTANCE c : $c = b \cos 11.5^\circ = 1.09$ in

DISTANCE e : $e = 1.11 \sin 11.5^\circ = .22$ in



MOMENTS ABOUT PRINCIPLE AXES

$$M_x = M \cos 11.5^\circ$$

$$M_y = M \sin 11.5^\circ$$

$$\sigma = \frac{M_x c}{I_x} + \frac{M_y (b+e)}{I_y}$$

$$\tau = \frac{2Th}{J}$$

$T = 500$ ft·lb

$$J = \left(\tfrac{1}{3}\right)(.91)\left[(.69)(.29)^3 + (2.67)(.45)^3 + (2.0)(.27)^3\right] = .0908\ in^4$$

NOTE: $2b_1 = .69$ in $\quad 2b_2 \approx 2.67$ in $\quad 2b_3 \approx 2.00$

$2h_1 = .29$ in $\quad 2h_2 \approx .45$ in $\quad 2h_3 \approx .27$

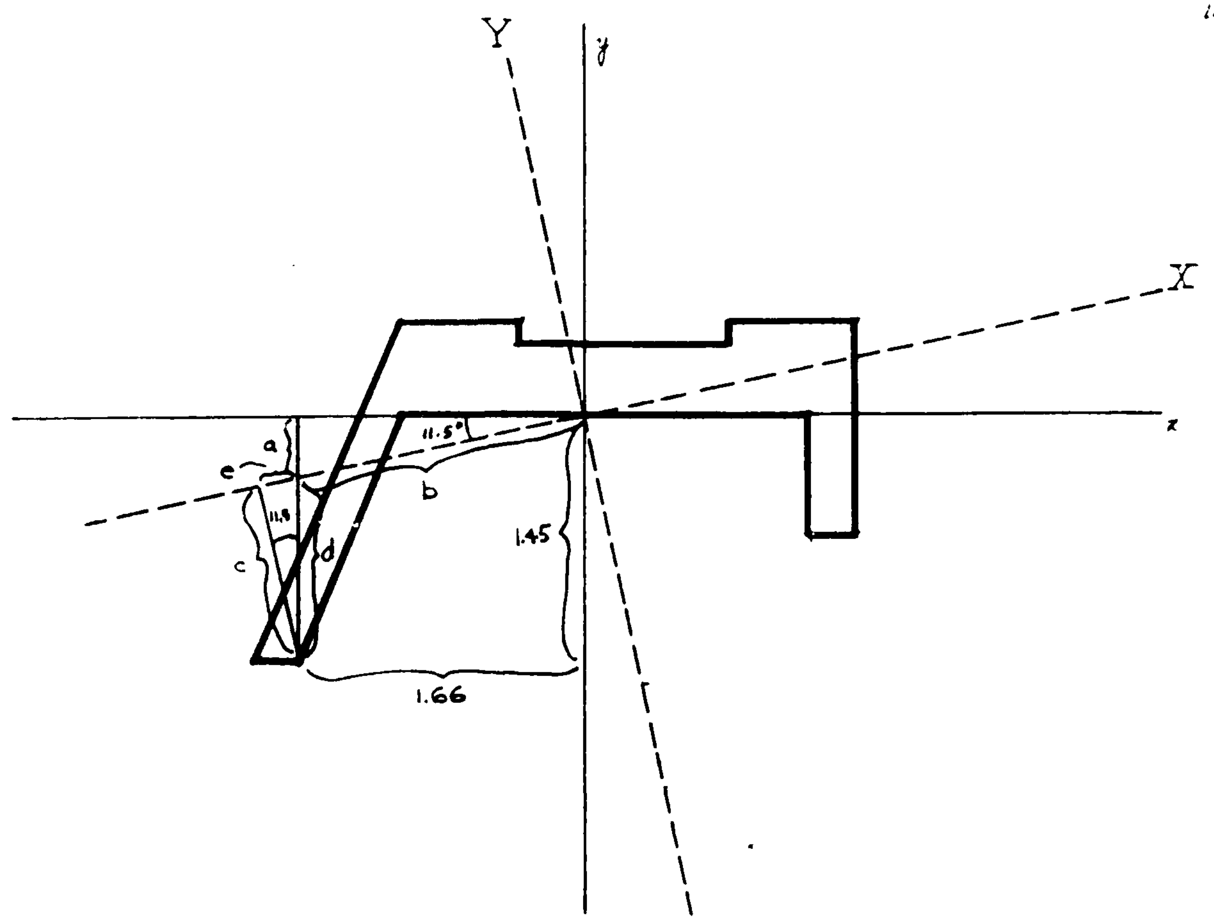


FIGURE 2 – CROSS-SECTION AT 237.440

1	0.00000	0.00000	7	3.51200	2.00000
2	.84000	2.00000	8	3.51200	.75000
3	1.54000	2.00000	9	3.22000	.75000
4	1.54000	1.87500	10	3.22000	1.44000
5	2.76000	1.87500	11	.84000	1.44000
6	2.76000	2.00000	12	.27000	0.00000

Y DISTANCE TO XX CENTROIDAL AXIS = 1.4491

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .4138

X DISTANCE TO YY CENTROIDAL AXIS = 1.9292

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS = 2.3011

TOTAL AREA = 1.9749

PRODUCT OF INERTIA = .4021

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = 2.3832

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .3317

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = 11.5 DEGREES

AT WORST CASE: $h = \frac{1}{2}t = (\frac{1}{2})(.27) = .14$ in

FOR BENDING STRESS:

$$\sigma = \frac{(M\cos 11.5^\circ)(1.09)}{2.3832} + \frac{(M\sin 11.5^\circ)(1.91)}{.3317}$$

$$M = \frac{\sigma}{\frac{(\cos 11.5)(1.09)}{2.3832} + \frac{(\sin 11.5)(1.91)}{.3317}}$$

$$M = .6265\,\sigma \quad \text{lb}\cdot\text{in}$$

APPLY MOHR'S CIRCLE EQUATIONS

$$\sigma_{max} = \frac{\sigma_{xx} + \overset{=0}{\cancel{\sigma_{yy}}}}{2} + \sqrt{\left(\tfrac{1}{4}\right)(\sigma_{xx} - \underset{=0}{\cancel{\sigma_{yy}}})^2 + \tau^2}$$

$$57000 = \frac{\sigma_{xx}}{2} + \sqrt{\left(\tfrac{1}{4}\right)(\sigma_{xx})^2 + \tau^2}$$

NOTE: $\tau = \frac{2Th}{J} = \frac{(2)(6000)(.14)}{.0908} = 18502$ psi

---

$$\left(57000 - \frac{\sigma_{xx}}{2}\right)^2 = \frac{1}{4}\sigma_{xx}^2 + (18502)^2$$

$$(57000)^2 - (2)\left(\frac{\sigma_{xx}}{2}\right)(57000) = (18502)^2$$

$$\sigma_{xx} = \frac{(57000)^2 - (18502)^2}{57000}$$

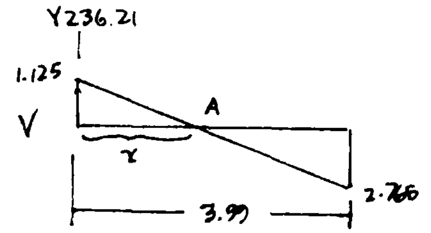
$$\sigma_{xx} = 50994 \text{ psi}$$

MAXIMUM MOMENT TO FAIL LONGERON

$$M_{max} = (.6265)(\sigma_{xx})$$

$$= (.6265)(50994) = 31948 \quad \text{in}\cdot\text{lb}$$

MOMENT AT Y237.440 — NOTE THAT THE MAXIMUM MOMENT OCCURS WHEN THE SHEAR EQUALS ZERO



USING SIMULAR TRIANGLES TO FIND A.

$$\frac{1.25}{x} = \frac{2.765}{3.99 - x} \Rightarrow x = 1.154$$

MOMENT IS TO BE INTEGRATED FROM Y233.700 to Y237.364

$$M = 3.075\omega + \int_{2.51}^{3.66} \omega(3.735 - x)\,dx$$

$$= 3.076\omega + \omega\left[3.735x - \tfrac{1}{2}x^2\right]\Big|_{2.51}^{3.66}$$

$$= 3.075\omega + .748\,\omega$$

$$= 3.823\,\omega$$

MAXIMUM FORCE PER UNIT LENGTH AT Y 237.364

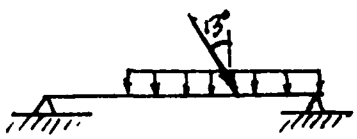
$$M = 3.823\omega$$

$$\omega = \frac{M_{max}}{3.823} = \frac{31\,948}{3.823}$$

$$\omega = 8357 \text{ lb/in}$$

MAXIMUM ALLOWABLE BIRDSTRIKE:

$$P_{max} = \frac{3.99\omega}{\cos 13^\circ} = \underline{\underline{34\,220 \text{ lb}}}$$



SHEAR STRESS ANALYSIS – UPPER LONGERON

SHEAR STRESS WILL BE ANALYZED AT TWO CRITICAL POINTS:

I. WEAKEST CROSS-SECTION OF THE LONGERON

II. POSITION ON LONGERON WHERE MAXIMUM SHEAR OCCURS.

NOTE(1): SHEAR STRESS "τ" HAS A PARABOLIC DISTRIBUTION THROUGH THE CROSS-SECTION. THEREFORE WHEN SHEAR STRESS IS A MAXIMUM, THE BENDING STRESS IS ZERO AND VICE VERSA. THUS SHEAR STRESS IS ANALYZED INDEPENDENT OF BENDING STRESS.

NOTE (2): SINCE LONGERON HAS UNSYMMETRICAL CROSS-SECTIONS, SHEAR STRESS WILL BE ANALYZED ALONG THE PRINCIPAL AXIS.

I. WEAKEST CROSS-SECTION → OCCURS BETWEEN Y236.210 AND Y236.950

THE POSITION WHERE THE LARGEST SHEAR IS LOCATED WILL BE ANALYZED. FROM SHEAR / MOMENT DIAGRAM, THIS WILL BE AT Y236.210

$V = 1.225\,\omega$ lb (SEE SECTION 1.1)

$$\tau = \frac{VQ}{It} + \tau_{\text{due to arch moment}}$$

Q = FIRST MOMENT OF INERTIA OF CROSS-SECTION ABOUT PRINCIPAL AXIS

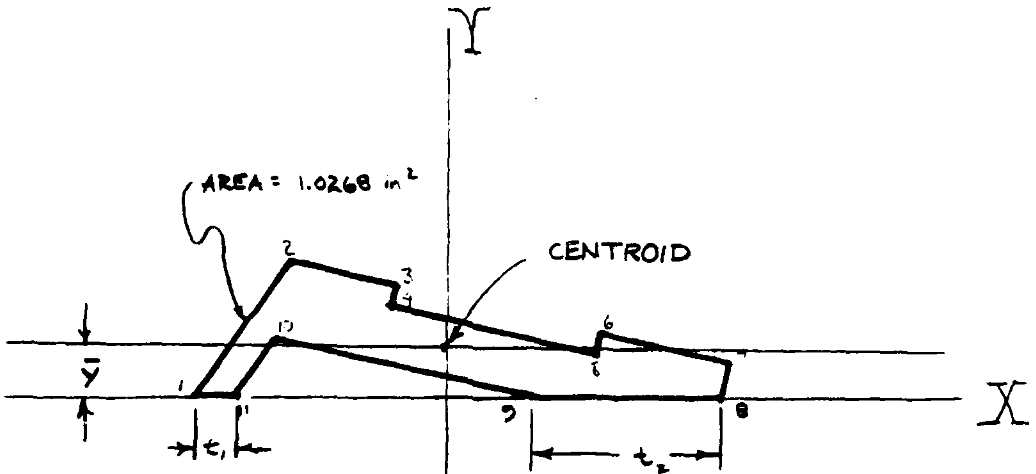
I = SECOND MOMENT OF INERTIA ABOUT PRINCIPAL AXIS OF THE WHOLE CROSS-SECTION

t = THICKNESS OF SECTION WHERE MAX SHEAR STRESS ACTS

<u>NOTE</u>: SHEAR STRESS DUE TO THE MOMENT (TORQUE) PRODUCED IN ARCH WHEN BIRDSTRIKE OCCURS WILL BE ASSUMED TO ADD AN ADDITIONAL SHEAR STRESS OF $\tau = 21000$ psi. THIS VALUE WAS SELECTED FROM PREVIOUS CALCULATED VALUE FOR A CROSS-SECTION OF SIMULAR SHAPE (Y236.940) (CALCULATED IN SECTION 1.1)

CROSS - SECTION Y236.210

POINT #	X	Y
1	−1.48	0
2	−.91	.79
3	−.30	.65
4	−.33	.52
5	.27	.24
6	.85	.39
7	1.64	.21
8	1.58	0
9	.50	0
10	−1.01	.35
11	−1.22	0



$\bar{y}$ = .2[illegible] in

$Q = A\bar{y} = (1.0268)(.296)$
$= .304 \text{ in}^3$

$t_1 = |x_1| - |x_{11}| = |-1.48| - |-1.22|$
$t_1 = .26$ in

$t_2 = x_8 - x_9 = 1.58 - .5$
$t_2 = 1.08$ in

Y DISTANCE TO XX CENTROIDAL AXIS	=	0.2956
MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS	=	0.0346
X DISTANCE TO YY CENTROIDAL AXIS	=	0.0218
MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS	=	0.7171
TOTAL AREA	=	1.0268
PRODUCT OF INERTIA	=	-0.0891
MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS	=	0.7285
MOMENT OF INERTIA ABOUT THE MINIMUM AXIS	=	0.0231
ANGLE FROM XX AXIS TO PRINCIPAL AXIS	=	-7.3 DEGREES

SEE DIAGRAMS FOR CALCULATIONS

$V = 1.225\,\omega$

$Q = .304 \text{ in}^3$

$t_1 + t_2 = 1.34 \text{ in}$

$I = 1.9918 \text{ in}^4$ (CALCULATED IN SECTION 1.1)

NOTE: "I" FOR SECTION Y236.210 IS THE SAME AS SECTION Y236.940

CROSS-SECTION WILL BE ANALYZED TO FAIL AT THE ULTIMATE SHEAR STRESS F_{su} (SEE TABLE FOR PROPERTIES OF 7075-T7351 - SECTION 6)

$F_{su} = 39000$ psi

$$\tau = F_{su} = \frac{VQ}{It} + 21000$$

$$39000 - 21000 = \frac{(1.225\,\omega)(.304)}{(1.9918)(t_1+t_2)} = \frac{(1.225\,\omega)(.304)}{(1.9918)(1.34)}$$

$$\omega = 129007 \text{ lb/in}$$

MAXIMUM BIRD STRIKE LOAD:

$$P_{max} = \frac{3.99\,\omega}{\cos 13^\circ} = \frac{(3.99)(129007)}{\cos 13^\circ}$$

$$\underline{\underline{P = 528280 \text{ lb}}}$$

II. POSITION OF MAXIMUM SHEAR — OCCURS JUST BEFORE Y240.200

MAXIMUM SHEAR: $V_{max} = 2.765\,\omega$

$$\tau = \frac{VQ}{It} + \tau_{\text{due to arch moment}}$$

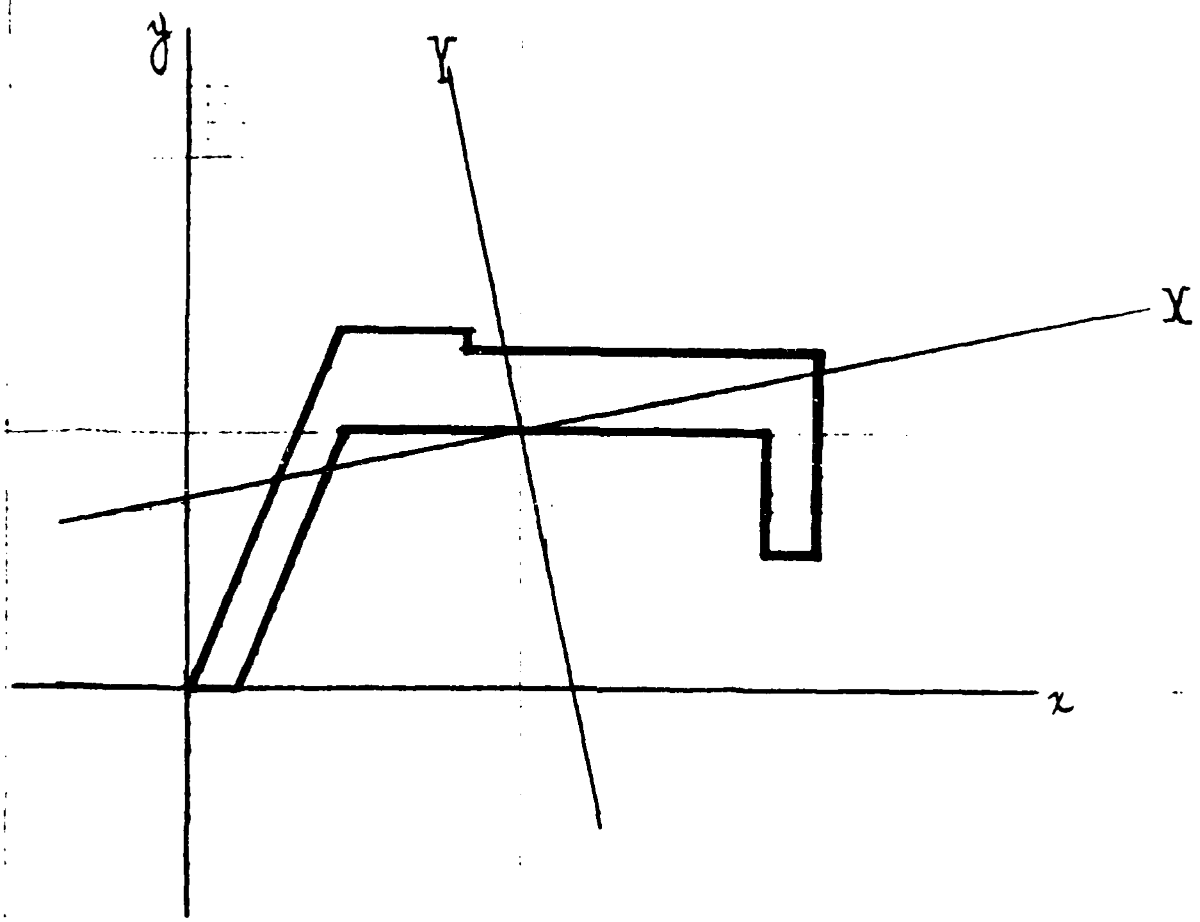
SEE DRAWING FOR CALCULATIONS OF Q, t

<u>NOTE</u>: THE SHEAR STRESS DUE TO ARCH MOMENT WILL BE ASSUMED TO ADD APPROXIMATELY 18 500 psi (THIS VALUE WAS CALCULATED IN SECTION 1.1 FOR THE SIMULAR CROSS-SECTION Y237.440)

CROSS-SECTION IS ANALYZED AT ULTIMATE SHEAR STRESS

$F_{su} = 39000$ psi

1.2.9



CROSS-SECTION OF UPPER LONGERON JUST BEFORE 240.200

1	0.00000	0.00000	6	3.51200	.75000
2	.84000	2.00000	7	3.22200	.75000
3	1.54200	2.00000	8	3.22200	1.44000
4	1.54200	1.87500	9	.84000	1.44000
5	3.51200	1.87500	10	.29000	0.00000

Y DISTANCE TO XX CENTROIDAL AXIS = 1.4178

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .4044

X DISTANCE TO YY CENTROIDAL AXIS = 1.8572

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS = 2.1788

TOTAL AREA = 1.8942

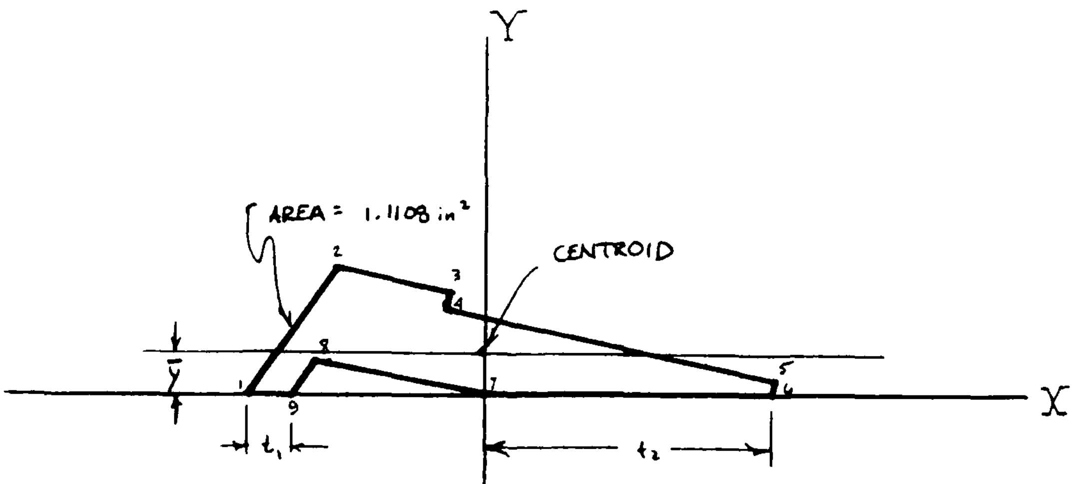
PRODUCT OF INERTIA = .3640

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = 2.2506

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .3326

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = 11.2 DEGREES

POINT #	X	Y
1	-1.39	0
2	-.88	.75
3	-.19	.61
4	-.22	.51
5	1.71	.09
6	1.69	0
7	0	0
8	-.97	.20
9	-1.11	0



$\bar{y} = .2672$ in

$Q = A\bar{y} = (1.1108)(.2672)$
$= .297 \text{ in}^3$

$t_1 = |x_1| - |x_9| = |-1.39| - |-1.11|$
$= .28$ in

$t_2 = x_6 - x_7 = 1.69 - 0$
$= 1.69$ in

1.2.7

CROSS-SECTION III

1	-1.39000	0.00000	6	1.69000	0.00000
2	-.88000	.75000	7	0.00000	0.00000
3	-.19000	.61000	8	-.97000	.20000
4	-.22000	.51000	9	-1.11000	0.00000
5	1.71000	.09000	****	-1	-1

Y DISTANCE TO XX CENTROIDAL AXIS - .2672

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS - .0351

X DISTANCE TO YY CENTROIDAL AXIS - -.0698

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS - .6105

TOTAL AREA - 1.1108

PRODUCT OF INERTIA - -.0742

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS - .6199

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS - .0257

ANGL⁻ FROM XX AXIS TO PRINCIPAL AXIS - -7.2 DEGREES

WOULD YOU LIKE TO CALCULATE
MOMENT OF INERTIA'S (Y OR N) . . . ?
N

$$F_{su} = 39000 = \frac{VQ}{I(t_1+t_2)} + 18500$$

$$\frac{(2.765\omega)(.297)}{(.6199)(1.69)} = 39000 - 18500$$

$$\omega = 26\,152 \ \text{lb/in}$$

MAXIMUM BIRDSTRIKE LOAD :

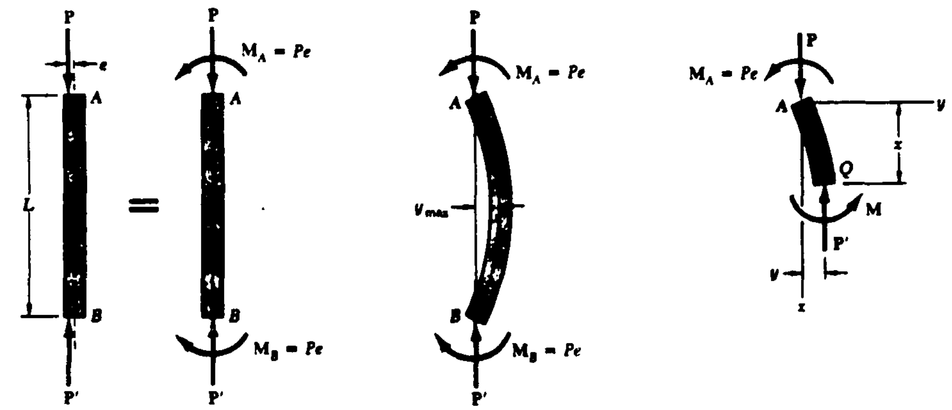
$$P_{max} = \frac{3.99\omega}{\cos 13°} = \frac{(3.99)(26152)}{\cos 13°}$$

$$P_{max} = \underline{\underline{107\,093 \ lb}}$$

BUCKLING ANALYSIS OF RIBS AT Y233.700 AND Y240.200

BUCKLING ANALYSIS – Columns Y233.700 Y240.200

WE WILL ASSUME THAT THE COLUMNS AT Y233.700 AND Y240.200 BEHAVE SIMULAR TO THE COLUMN IN THE DIAGRAM BELOW. ALTHOUGH THE COLUMNS BEING ANALYZED ARE INITIALLY CURVED THE EQUATIONS STILL APPLY.



WE WILL USE THE SECANT FORMULA TO ANALYZE THE MAXIMUM BUCKLING LOAD/STRESS. (FOR FURTHER DETAILS SEE <u>MECHANICS OF MATERIALS</u>, pgs 541-544 IN SECTION 6)

$$\frac{P}{A} = \frac{\sigma_{max}}{1 + \frac{ec}{\rho^2} \sec\left(\frac{1}{2}\sqrt{\frac{P}{EA}}\,\frac{L'}{\rho}\right)}$$

P = APPLIED LOAD
A = AREA OF CROSS-SECTION BEING ANALYZED
e = ECCENTRICITY, CALCULATED PREVIOUSLY
C = DISTANCE FROM MOMENT OF INERTIA AXIS TO THE OUTER EDGE OF THE COLUMN CROSS-SECTION ON THE INSIDE RADIUS OF COLUMN
ρ = RADIUS OF GYRATION = $\sqrt{I/A}$
E = MODULUS OF COLUMN
L' = EFFECTIVE LENGTH OF COLUMN
σ_{max} = MAXIMUM COMPRESSIVE STRESS = F_{cy}
F_c = CRITICAL BUCKLING STRESS

<u>NOTE</u>: THE ABOVE EQUATION MUST BE SOLVED USING A TRIAL AND ERROR SOLUTION.

BUCKLING WILL BE CALCULATED FOR THE WEAKEST CROSS-SECTION IN THE COLUMNS.

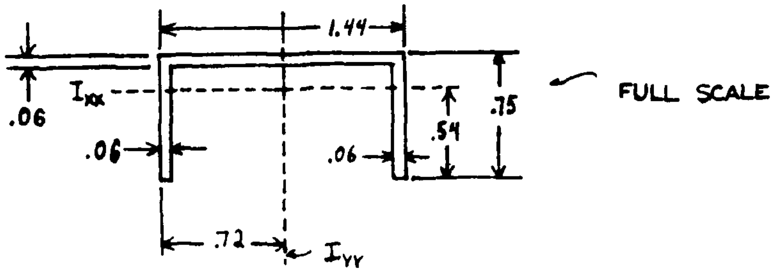
HP PROGRAM FOR SOLVING SECANT FORMULA - NOT CONSIDERING EFFECT OF ARCH MOMENT

```
LBL D                 *
RCL 01   (e)          180
RCL 02   (c)          *
*                     π
RCL 03   (ρ)          ÷
x²                    cos
÷                     1/x
STO 04                RCL 04
RCL 20   (P)          *
RCL 05   (E)          1.0
÷                     +
RCL 06   (A)          1/x
÷                     RCL 08   (Fcy)
√x                    *
.5                    RCL 06   (A)
*                     *
RCL 07   (L')         RTN
RCL 03   (ρ)
÷
```

HP PROGRAM FOR SOLVING SECANT FORMULA - INCLUDING EFFECT OF ARCH MOMENT

```
LBL C                 ÷                     +
RCL 01   (e)          √x                    1/x
RCL 10   (M)          .5                    RCL 08   (Fcy)
                      *                     *
RCL 20   (P)          RCL 07   (L')         RCL 06   (A)
÷                     RCL 03   (ρ)          *
-                     ÷                     RTN
RCL 02   (c)          *
*                     180
RCL 03   (ρ)          *
x²                    π
÷                     ÷
STO 04                cos
RCL 20   (P)          1/x
RCL 05   (E)          RCL 04
÷                     *
RCL 06   (A)          1.0
```

CROSS-SECTION OF RIB (SECTION AA) -- Y233.700 — ASSUMED TO BE THE WEAKEST CROSS-SECTION



Y DISTANCE TO XX CENTROIDAL AXIS = .5365

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .0093

X DISTANCE TO YY CENTROIDAL AXIS = .7200

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS = .0544

TOTAL AREA = .1692

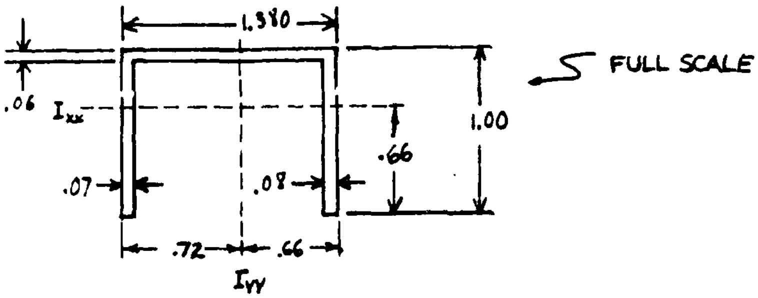
PRODUCT OF INERTIA = .0000

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = .0544

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .0093

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = .0 DEGREES

CROSS-SECTION OF RIB (SECTION EE) -- Y240.200 — ASSUMED TO BE THE WEAKEST CROSS-SECTION



Y DISTANCE TO XX CENTROIDAL AXIS = .6550

MOMENT OF INERTIA ABOUT XX CENTROIDAL AXIS = .0234

X DISTANCE TO YY CENTROIDAL AXIS = .7158

MOMENT OF INERTIA ABOUT YY CENTROIDAL AXIS = .0731

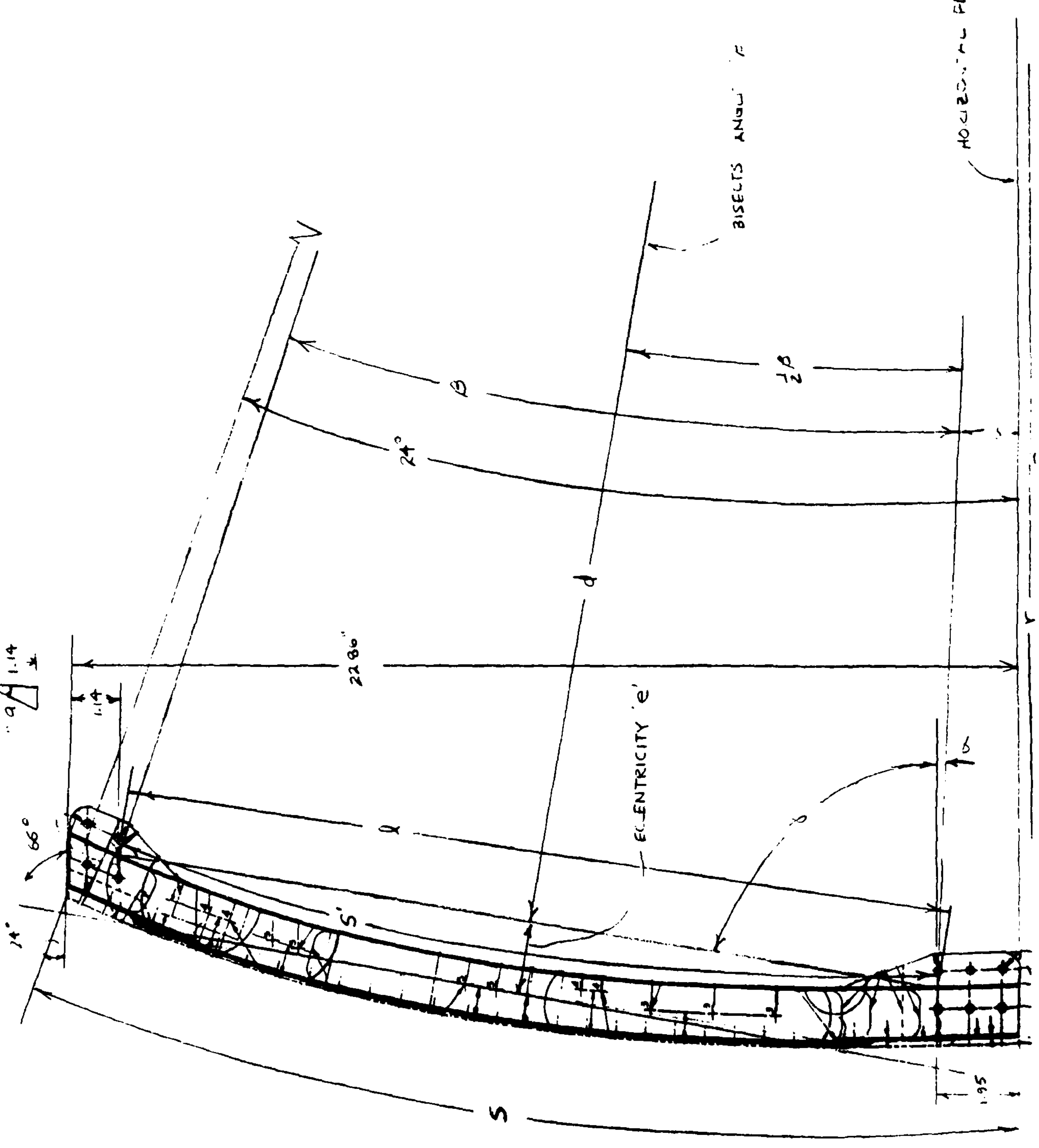
TOTAL AREA = .2238

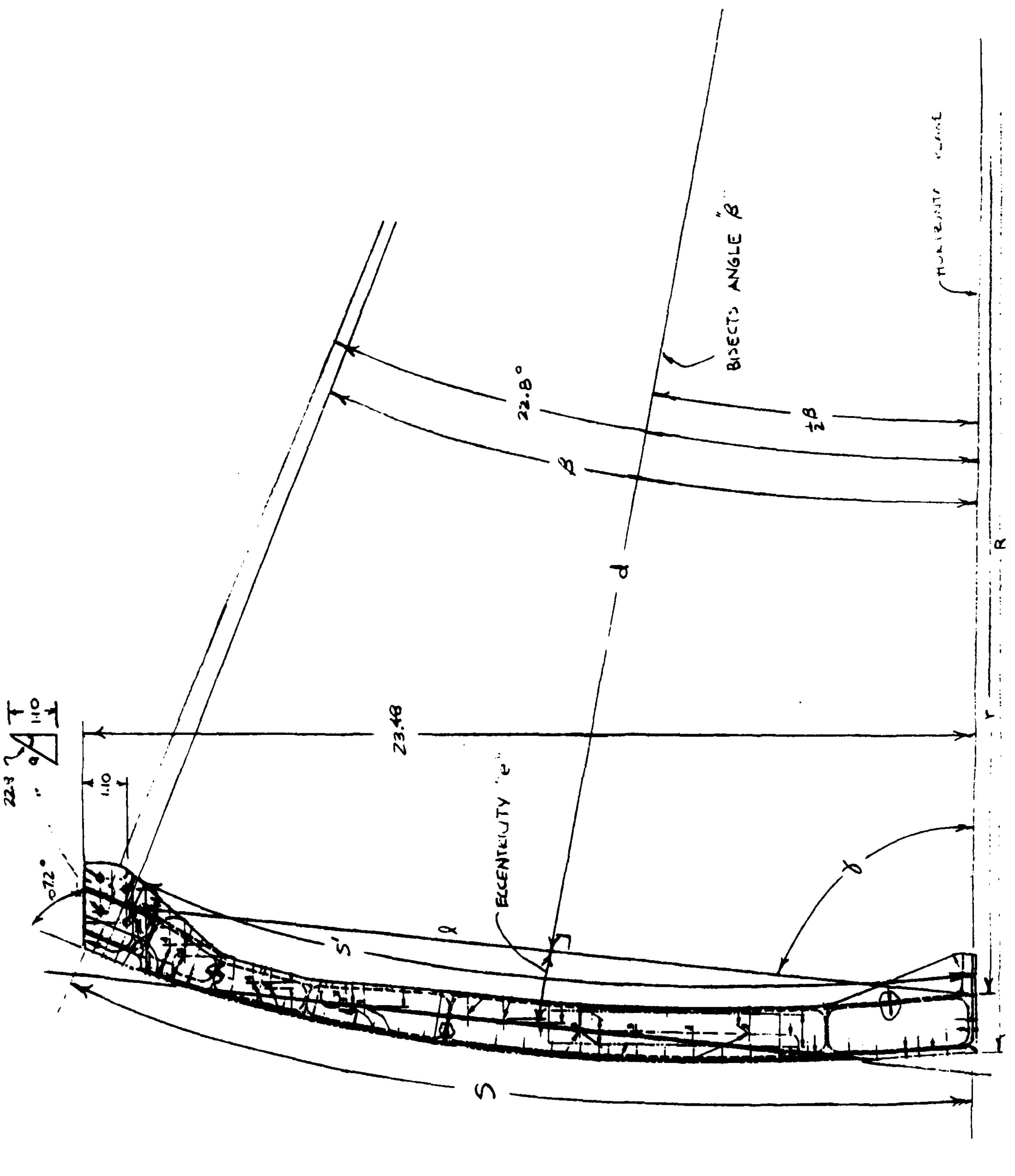
PRODUCT OF INERTIA = -.0011

MOMENT OF INERTIA ABOUT THE PRINCIPAL AXIS = .0731

MOMENT OF INERTIA ABOUT THE MINIMUM AXIS = .0234

ANGLE FROM XX AXIS TO PRINCIPAL AXIS = -1.2 DEGREES


BISECTS ANGLE
ECCENTRICITY 'e'
22.86"
24°
66°
14°
1.14
1.95
S
S'
d


BISECTS ANGLE "β"
22.8°
½β
β
d
23.48
1.10
ECCENTRICITY "e"
0.72°
S'
S
α
γ
R

BUCKLING ANALYSIS -

I. RIB AT Y233.700

l = APPROXIMATION OF THE LENGTH OF COLUMN BEING ANALYZED.

S = ARC LENGTH OF THE OUTER SURFACE OF THE COLUMN

S' = ARC LENGTH OF THE INNER SURFACE OF THE COLUMN

e = ECCENTRICITY ; DISTANCE LOAD IS OFFSET FROM THE ASSUMED AXIS OF SYMMETRY

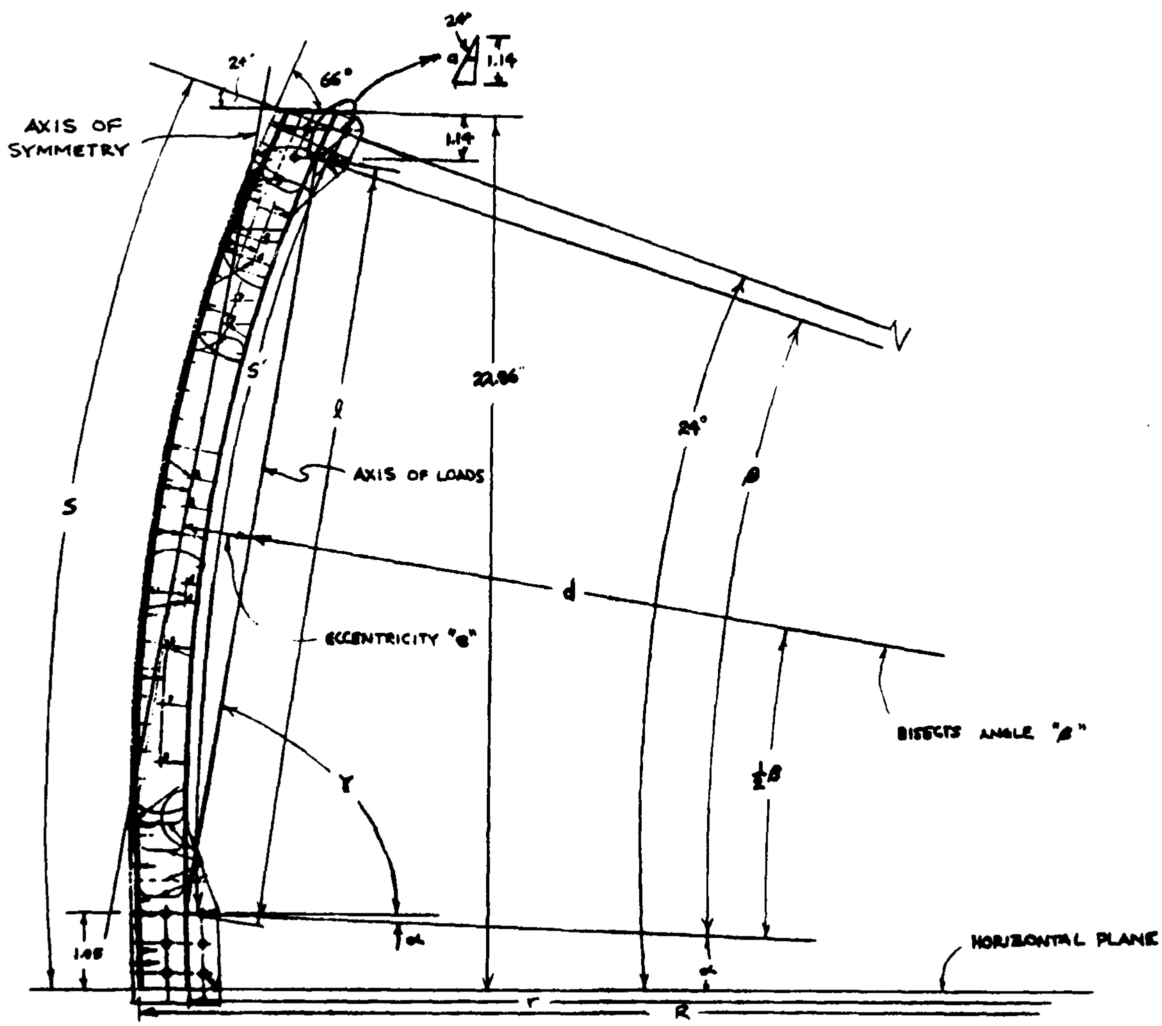
γ = ANGLE AT WHICH THE BUCKLING LOADS ACT ON THE COLUMN WITH RESPECT TO THE HORIZONTAL AXIS.

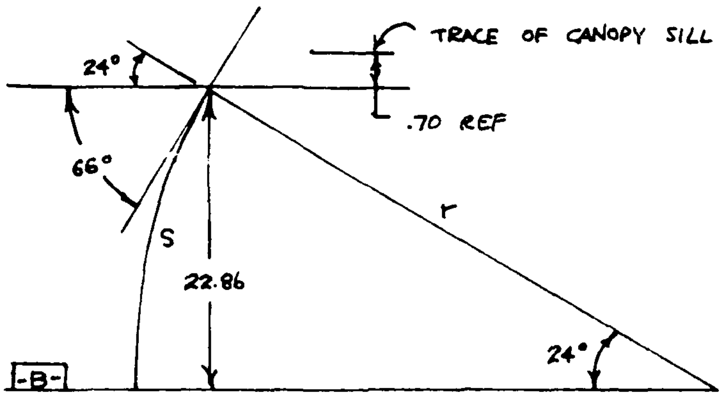
R = RADIUS TO THE ARC LENGTH S

r = RADIUS TO THE ARC LENGTH S'

β = ANGLE THAT DEFINES ARC LENGTH S' AT A RADIUS r.

d = PERPENDICULAR DISTANCE FROM THE AXIS OF LOADS TO THE ORIGIN





$\sin 24° = \dfrac{22.86}{R}$

$R = 56.20$ in

$S = R\theta$ $\quad \theta$ IN RADIANS

$S = (56.20)\left(24 \cdot \frac{\pi}{180}\right)$

$S = 23.54$ in

CALCULATING SMALL ARC LENGTH s'

$r = R - 1.44$ NOTE: 1.44 = CHANNEL WIDTH

$r = 56.20 - 1.44$

$r = 54.76$ in

$a = 1.14 / \cos 24°$

$a = 1.25$ in

ARC LENGTH s': $s' = s - a - 1.95$

$= 23.54 - 1.25 - 1.95$

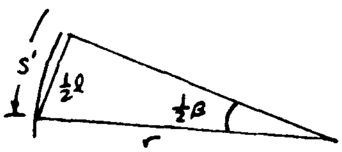
$= 20.34$ in

CALCULATING ANGLE β:

$s' = r\beta$

$\beta = \dfrac{s'}{r} = \left(\dfrac{20.34}{54.76}\right)\left(\dfrac{180}{\pi}\right) = 21.28°$

CALCULATING THE APPROXIMATE LENGTH ℓ:



$\sin\left(\frac{1}{2}\beta\right) = \dfrac{\frac{1}{2}\ell}{r}$

$\ell = 2r\sin\left(\frac{1}{2}\beta\right)$

$= (2)(54.76)\sin 10.64°$

$\ell = 20.22$ in

CALCULATING ECCENTRICITY

$\cos\left(\frac{1}{2}\beta\right) = \dfrac{d}{r}$

$d = r\cos\frac{1}{2}\beta$

$= 54.76 \cos 10.64°$

$= 53.82$

$e = (r - d) + .72$

$= (54.76 - 53.82) + .72$

$= 1.66$ in

NOTE: $.72 = \frac{1}{2}$ CHANNEL WIDTH (CHANNEL IS SYMMETRIC)

CALCULATING AXIS OF LOADS

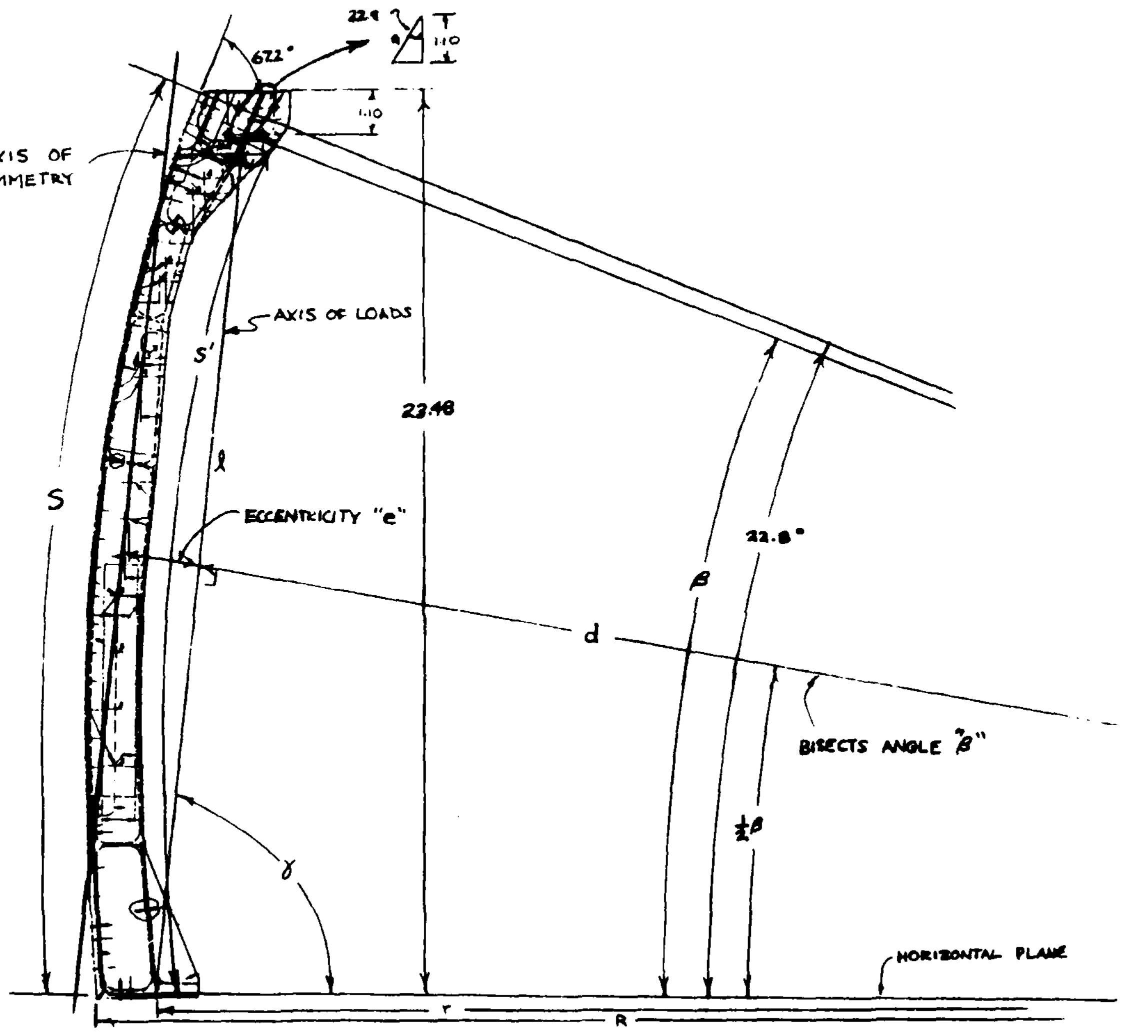
$1.95 = R\alpha$

$\alpha = \left(\dfrac{1.95}{56.20}\right)\left(\dfrac{180}{\pi}\right) = 1.99°$

$\gamma = (180 - 90 - \frac{1}{2}\beta) - \alpha$

$\gamma = 77.4°$

II. RIB AT Y240.200



DEFINITIONS: SAME AS RIB Y233.700

CALCULATING OUTER ARC-LENGTH S:

$$R = \frac{23.48}{\sin 22.83°}$$

$$R = 60.52 \text{ in}$$

$$S = R\Theta$$

$$= (60.52)\left(22.83 \cdot \frac{\pi}{180}\right)$$

$$= 24.12 \text{ in}$$

CALCULATING INNER ARC-LENGTH S':

$$a = \frac{1.10}{\cos 22.83°}$$

$$a = 1.19$$

$$S' = S - a$$

$$= 24.12 - 1.19$$

$$= 22.93 \text{ in}$$

CALCULATING ANGLE β:

$r = R - 1.38$

$r = 59.14$ in

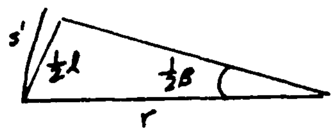
$s' = r\beta$

$\beta = s'/r$

$\beta = \left(\frac{22.93}{59.14}\right)\left(\frac{180}{\pi}\right) = 22.21°$

NOTE: 1.38 = CHANNEL WIDTH

CALCULATING APPROXIMATE LENGTH ℓ:



$\sin(\tfrac{1}{2}\beta) = \frac{\frac{1}{2}\ell}{r}$

$\ell = 2r \sin \tfrac{1}{2}\beta$

$\ell = (2)(59.14)\sin(11.11°)$

$\ell = 22.79$ in

CALCULATING ECCENTRICITY:

$\cos(\tfrac{1}{2}\beta) = \frac{d}{r}$

$d = r\cos\tfrac{1}{2}\beta$

$d = 58.03$ in

$e = (r-d) + .66$

$e = (59.14 - 58.03) + .66$

$e = 1.71$ in

NOTE: .993 = DISTANCE TO I_{yy}

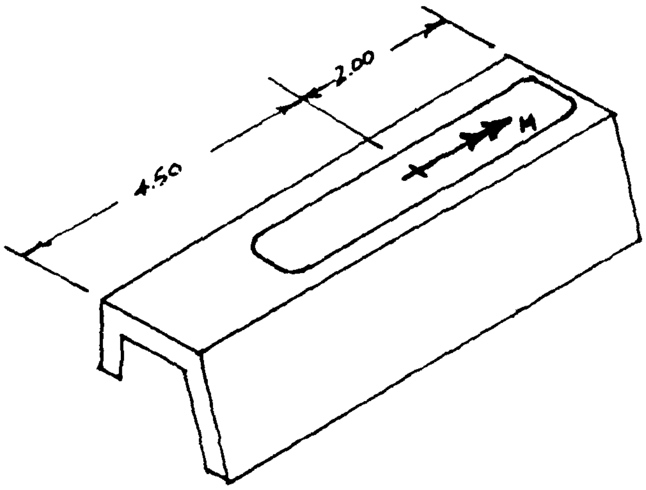
CALCULATING AXIS OF LOADS:

$\gamma = 180 - 90 - \tfrac{1}{2}\beta$

$\gamma = 90 - 11.11°$

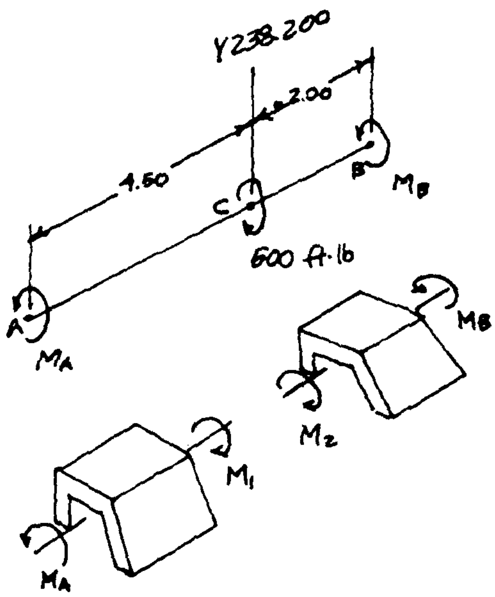
$\gamma = 78.9°$

BUCKLING ANALYSIS — Determining distributed moment from arch along longeron. These moments will be applied to columns Y233.700 AND Y240.200



ASSUME THAT THE MOMENT OF THE ARCH IS APPLIED AT THE MIDDLE OF THE FOOT THAT CONNECTS THE ARCH TO THE LONGERON.

ASSUME THE BOTH ENDS OF THE LONGERON ARE FIXED IN THE PLANE OF ROTATION OF THE MOMENT. THUS WE HAVE A STATICALLY INDETERMINATE STRUCTURE.



M_B = MOMENT AT COLUMN Y240.200 (INTERNAL)
M_A = MOMENT AT COLUMN Y233.700 (INTERNAL)
G = TORSIONAL RIGIDITY
J = POLAR MOMENT OF INERTIA
ϕ_1 = ANGULAR DEFLECTION OF LONGERON DUE TO M_1.
ϕ_2 = ANGULAR DEFLECTION OF LONGERON DUE TO M_2
L = LENGTH OF LONGERON BEING CONSIDERED

NOTE: TOTAL ANGULAR DEFLECTION (TWIST) MUST EQUAL ZERO SINCE BOTH ENDS ARE FIXED.

$$\phi_1 + \phi_2 = \phi = 0 \qquad \underline{\text{NOTE}}: \quad \phi = \frac{ML}{JG}$$

<u>NOTE</u>: INTERNAL MOMENT M_1 IS EQUAL TO M_A
INTERNAL MOMENT M_2 IS EQUAL TO M_B

$$\frac{(M_A)(4.50)}{J_1 G} - \frac{(M_B)(2.00)}{J_2 G} = 0$$

<u>NOTE</u>: MINUS SIGN BECAUSE SECTION AC AND SECTION CB ARE TWISTED IN <u>OPPOSITE</u> DIRECTIONS

$$\frac{(M_A)(4.50)}{J_1 G} = \frac{(M_B)(2.00)}{J_2 G}$$

$$M_A = \left(\frac{2.00}{4.50}\right)\left(\frac{J_1}{J_2}\right) M_B$$

<u>NOTE:</u> IT WILL BE ASSUMED THAT THE POLAR MOMENTS OF INERTIA J_1 AND J_2 ARE CONSTANT THROUGHOUT SECTIONS AC AND CB RESPECTIVELY (ACTUALLY, THESE VALUES VARY ALONG THE LONGERON). THE WORST "J" IN SECTION AC AND SECTION CB WILL BE ANALYZED. THESE VALUES HAVE BEEN CALCULATED IN THE FAILURE ANALYSIS OF THE UPPER LONGERON. (SEE SECTION 1.1)

WORST "J" FOR SECTION AC → BETWEEN POSITIONS Y236.210 AND Y236.945

$J_1 = .0666 \ in^4$

WORST "J" FOR SECTION CB → BETWEEN POSITIONS Y237.045 AND Y238.445

$J_2 = .0908 \ in^4$

$$M_A = \left(\frac{2.00}{4.50}\right)\left(\frac{.0666}{.0908}\right) M_B$$

$$= .326 \ M_B$$

$M = M_A + M_B$

$6000 \ in \cdot lb = M_A + M_B$

$6000 = .326 \ M_B + M_B$

$\longrightarrow M_B = 4525 \ in \cdot lb$

$\longrightarrow M_A = (.326)(4525) = 1475 \ in \cdot lb$

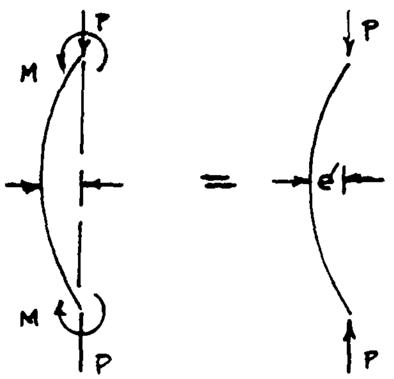
MOMENT APPLIED TO COLUMN Y233.700 → $M_A = 1475 \ in \cdot lb$

MOMENT APPLIED TO COLUMN Y240.200 → $M_B = 4525 \ in \cdot lb$

THESE VALUES WILL BE USED TO CALCULATE MAXIMUM BIRDSTRIKE LOADS FOR COLUMNS Y233.700 AND Y240.200.

BUCKLING ANALYSIS – Considering effect of moment produced by arch upon birdstrike Calculated w/out effect of skin

THE MOMENT PRODUCED BY THE ARCH WILL DECREASE THE ECCENTRICITY DISTANCE e AND THUS INCREASE THE BUCKLING LOAD REQUIRED FOR FAILURE



e' = EFFECTIVE ECCENTRICITY

e = CALCULATED ECCENTRICITY

$$Pe' = Pe - M$$

$$e' = e - \frac{M}{P}$$

THE SECANT FORMULA WILL BE USED TO CALCULATE THE MAXIMUM BUCKLING LOAD. THE EFFECTIVE ECCENTRICITY e' WILL BE USED INSTEAD OF THE CALCULATED ECCENTRICITY e. IN THE FORMULA

$$\frac{P}{A} = \frac{\sigma_{max}}{1 + \frac{e'c}{\rho^2}\sec\left[\frac{1}{2}\sqrt{\frac{P}{EA}}\,\frac{L'}{\rho}\right]}$$

NOTE: IT WILL BE ASSUMED THAT A 500 ft·lb MOMENT IS APPLIED BY THE ARCH AND IS DISTRIBUTED AS CALCULATED IN SECTION 2.4

$$\frac{P}{A} = \frac{\sigma_{max}}{1 + \frac{(e - \frac{M}{P})c}{\rho^2}\sec\left[\frac{1}{2}\sqrt{\frac{P}{EA}}\,\frac{L'}{\rho}\right]}$$

I. FOR COLUMN Y233.700

$A = .1692\ in^2$	$L = 20.22\ in$	$E = 10.3 \times 10^6\ psi$
$e = 1.66\ in$	$I = .0544\ in^4$	$\sigma_{max} = F_{cy} = 56000\ psi$
$c = .72\ in$	$\rho = .567\ in$	$L' = .7L = 14.16\ in$

(A) APPLIED MOMENT : $M_A = 1475\ in \cdot lb$

$$\frac{P}{.1692} = \frac{56000}{1 + \frac{(1.66 - \frac{1475}{P})(.72)}{(.567)^2} \sec\left[\frac{1}{2}\sqrt{\frac{P}{(E)(.1692)}}\left(\frac{14.16}{.567}\right)\right]}$$

$P = 2545$ lb

$F_c = \frac{P}{A} = \frac{2545}{.1692} = 15041$ psi

II. COLUMN Y240.200 — ASSUME PINNED/PINNED CONDITION

$A = .2238\ in^2$	$L = 22.79$ in	$E = 10.3 \times 10^6$ psi
$e = 1.71$ in	$I = .0731\ in^4$	$\sigma_{max} = F_{cy} = 56000$ psi
$c = .66$ in	$\rho = .572$ in	$L' = L = 22.79$ in

APPLIED MOMENT : $M_B = 4525$ in·lb

$$\frac{P}{.2238} = \frac{56000}{1 + \frac{(1.71 - \frac{4525}{P})(.66)}{(.572)^2} \sec\left[\frac{1}{2}\sqrt{\frac{P}{(E)(.2238)}}\left(\frac{22.79}{.572}\right)\right]}$$

$P = 4230$ lb

$F_c = \frac{P}{A} = \frac{4230}{.2238} = 18900$ psi

III. COLUMN Y240.200 — ASSUME FIXED / PINNED CONDITION

PROPERTIES SAME AS ABOVE EXCEPT

$L' = .7L = 15.95$ in

$$\frac{P}{.2238} = \frac{56000}{1 + \frac{(1.71 - \frac{4525}{P})(.66)}{(.572)^2} \sec\left[\frac{1}{2}\sqrt{\frac{P}{(E)(.2239)}}\left(\frac{15.95}{.572}\right)\right]}$$

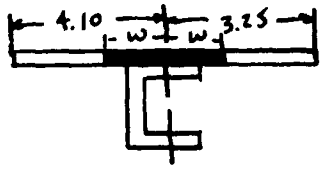
$P = 4535$ lb

$F_c = \frac{P}{A} = \frac{4535}{.2238} = 20265$ psi

BUCKLING ANALYSIS - Calculated w/ effect of skin and including effect of moment produced by the arch.

THE BUCKLING LOADS WILL BE CALCULATED IN THE PREVIOUS MANNER. ONLY THE EFFECT OF THE .063 in SKIN WILL BE CALCULATED SINCE THIS THICKNESS OF SKIN ACTUALLY COVERS THE RIB.

I. FOR COLUMN Y233.700



$A = .1692\ in^2$

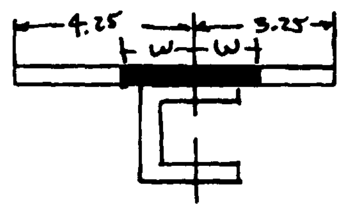
$F_c = 15041\ psi$

CALCULATE EFFECTIVE WIDTH: $\omega = .60t\sqrt{\frac{E}{F_c}} = (.6)(.063)\sqrt{\frac{E}{15041}} = .989\ in$

CALCULATE TOTAL AREA $A_t = A + 2\omega t = .1692 + (2)(.989)(.063) = .294\ in^2$

CALCULATE COMPRESSIVE LOAD (FOR BUCKLING) $R = F_c A_t = (15041)(.294) = 4420\ lb$

II. FOR COLUMN Y240.200



A. PINNED/PINNED CONDITION

$A = .2238\ in^2$

$F_c = 18900\ psi$

EFFECTIVE WIDTH: $\omega = (.6)(.063)\sqrt{\frac{E}{18900}} = .882\ in$

TOTAL AREA: $A_t = A + 2\omega t = .2238 + (2)(.882)(.063) = .335\ in^2$

COMPRESSIVE LOAD (FOR BUCKLING) $R = A_t F_c = (.335)(18900) = 6330\ lb$

B. FIXED/PINNED CONDITION

$A = .2238\ in^2$

$F_c = 20265\ psi$

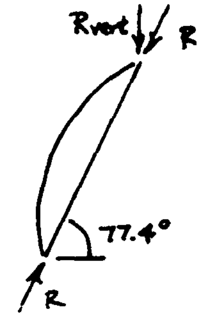
EFFECTIVE WIDTH: $\omega = (.6)(.063)\sqrt{\frac{E}{20265}} = .852\ in$

TOTAL AREA: $A_t = .2238 + (2)(.852)(.063) = .331 \ in^2$

COMPRESSIVE LOAD (FOR BUCKLING) $R = F_c A_t = (.331)(20265) = 6710 \ lb$

BUCKLING ANALYSIS – Calculation of the allowable vertical load on the longeron. Includes effect of moment produced by the arch.

I. ALLOWABLE VERTICAL LOAD FOR BUCKLING OF Y 233.700



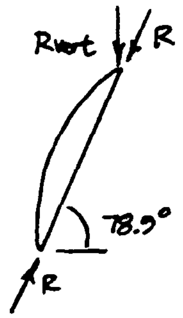
$R_{vert} = R \sin 77.4° = 4420 \sin 77.4 = 4315$ lb

$R_{Hor} = R \cos 77.4° = 4420 \cos 77.4 = 964$ lb

VERTICAL TRANSMITTED FORCE CANNOT EXCEED

$R_{vert} = 4315$ lb

II. ALLOWABLE VERTICAL LOAD FOR BUCKLING OF Y 240.200



A. FOR PINNED / PINNED CONDITION

$R_{vert} = R \sin 78.9° = 6330 \sin 78.9° = 6212$ lb

$R_{Hor} = R \cos 78.9° = 6330 \cos 78.9° = 1219$ lb

VERTICAL TRANSMITTED FORCE CANNOT EXCEED

$R_{vert} = 6212$ lb

B. FOR FIXED / PINNED CONDITION

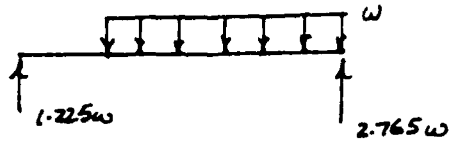
$R_{vert} = R \sin 78.9° = 6710 \sin 78.9° = 6585$ lb

$R_{hor} = R \cos 78.9° = 6710 \cos 78.9° = 1292$ lb

VERTICAL TRANSMITTED LOAD CANNOT EXCEED

$R_{vert} = 6585$ lb

BUCKLING ANALYSIS - Maximum Allowable Birdstrike load for buckling failure in columns Y233.700 and Y240.200. Includes effect of arch moment.



I. MAXIMUM BIRDSTRIKE AT Y233.700

MAX VERTICAL BUCKLING LOAD AT Y233.700 → $R_{vert} = 4315$ lb

$1.225w = R_{vert} = 4315$ $\qquad$ $P_{vert} = 3.99w$

$w = 3522$ lb/in $\qquad$ $= (3.99)(3522) = 14055$ lb

$$P_{max} = \frac{P_{vert}}{\cos 13^\circ} = \frac{14055}{\cos 13^\circ} = \underline{\underline{14424 \text{ lb}}} \quad \left(\begin{matrix}\text{MAXIMUM}\\ \text{BIRDSTRIKE}\end{matrix}\right)$$

II. MAXIMUM BIRDSTRIKE AT Y240.200

A. FOR PINNED / PINNED CONDITION

MAXIMUM VERTICAL BUCKLING LOAD AT Y240.200 → $R_{vert} = 6212$ lb

$2.765w = R_{vert} = 6212$ $\qquad$ $P_{vert} = 3.99w$

$w = 2247$ lb/in $\qquad$ $= (3.99)(2247) = 8964$ lb

$$P_{max} = \frac{P_{vert}}{\cos 13^\circ} = \frac{8964}{\cos 13^\circ} = \underline{\underline{9200 \text{ lb}}} \quad \left(\begin{matrix}\text{MAXIMUM}\\ \text{BIRDSTRIKE}\end{matrix}\right)$$

B. FOR FIXED/PINNED CONDITION

MAX VERTICAL BUCKLING LOAD AT Y240.200 → $R_{vert} = 6585$ lb

$2.765w = R_{vert} = 6585$ $\qquad$ $P_{vert} = 3.99w$

$w = 2382$ lb/in $\qquad$ $= (3.99)(2382) = 9502$ lb

$$P_{max} = \frac{P_{vert}}{\cos 13^\circ} = \frac{9502}{\cos 13^\circ} = \underline{\underline{9752 \text{ lb}}} \quad \left(\begin{matrix}\text{MAXIMUM}\\ \text{BIRDSTRIKE}\end{matrix}\right)$$

CRIPPLING ANALYSIS OF RIBS AT Y233.700 AND Y240.200

CRIPPLING ANALYSIS

COLUMNS WILL BE ANALYZED FOR LOCAL CRIPPLING AT THE WEAKEST CROSS-SECTION. THE CALCULATIONS WERE DONE FOLLOWING THE INFORMATION AND EXAMPLES CONTAINED IN SECTION 14.14 OF THE BOOK "AIRCRAFT STRUCTURES". WEAKEST CROSS-SECTIONS ARE THOSE FOUND IN SECTION 2.1.

THE FOLLOWING FIGURES WERE USED TO CALCULATE CRIPPLING STRESS.

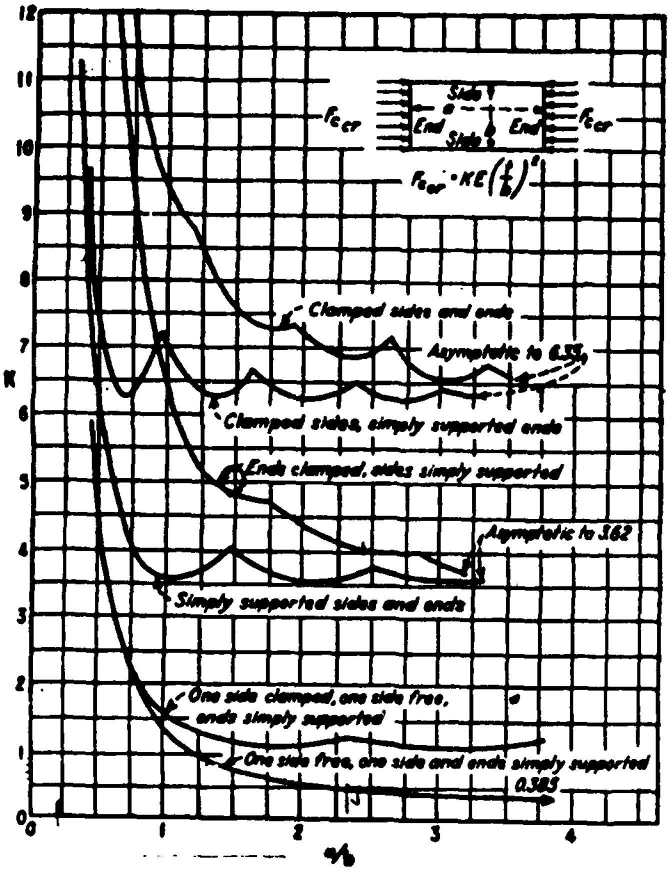


FIGURE 1 - VALUES OF "K" FOR VARIOUS SUPPORT CONDITIONS OF FLAT PLATES IN COMPRESSION

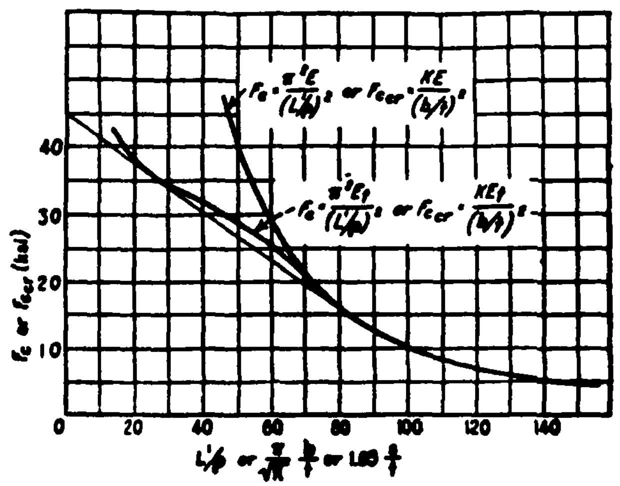


FIGURE 2 — ALLOWABLE BUCKLING STRESSES FOR A FLAT PLATE IN THE PLASTIC OR SHORT COLUMN RANGE

NOTE: THE VALUE OF F_{cc} (OR σ_{cc}) CAN BE OBTAINED FOR ANY KNOWN VALUE OF $\frac{\pi}{\sqrt{K}}\left(\frac{b}{t}\right)$

EACH COLUMN WILL BE ANALYZED AS 3 FLAT PLATES. THE EFFECT OF THE SKIN WILL ALSO BE INCLUDED IN THE ANALYSIS.

I. FOR COLUMN Y233.700

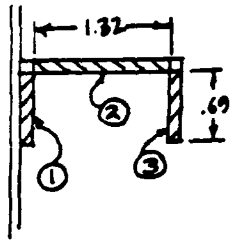


PLATE 1 – ASSUMED THAT BOTH ENDS AND ONE SIDE ARE SIMPLY SUPPORTED, ONE SIDE FREE

PLATE 2 – ASSUMED THAT BOTH ENDS AND SIDES ARE SIMPLY SUPPORTED.

PLATE 3 – ASSUMED BOTH ENDS AND ONE SIDE ARE SIMPLY SUPPORTED, ONE SIDE FREE

LENGTH OF COLUMN Y233.700 = 20.22 in

FROM FIGURE 1 :

PLATE 1 – $\frac{a}{b} = \frac{1.32}{.69} = 1.91 \rightarrow K_1 = 0.57$

PLATE 2 – $\frac{a}{b} = \frac{1.32}{1.32} = 1.0 \rightarrow K_2 = 3.62$

PLATE 3 – $\frac{a}{b} = \frac{1.32}{.69} = 1.91 \rightarrow K_3 = 0.57$

CALCULATING ALLOWABLE CRIPPLING STRESS FOR EACH PLATE (FIGURE 2)

PLATE 1 : $\frac{\pi}{\sqrt{K_1}}\frac{b}{t} = \frac{\pi}{\sqrt{.57}}\left(\frac{.69}{.06}\right) = 47.8 \rightarrow \sigma_{cc_1} = 29\,000$ psi

PLATE 2 : $\frac{\pi}{\sqrt{K_2}}\frac{b}{t} = \left(\frac{\pi}{\sqrt{3.62}}\right)\left(\frac{1.32}{.06}\right) = 36.3 \Rightarrow \sigma_{cc_2} = 32000$ psi

PLATE 3 : $\frac{\pi}{\sqrt{K_3}}\frac{b}{t} = \left(\frac{\pi}{\sqrt{.57}}\right)\left(\frac{.69}{.06}\right) = 47.8 \rightarrow \sigma_{cc_3} = 29\,000$ psi

CALCULATING TOTAL CRIPPLING STRESS

$$\sigma_{cc} = \frac{\Sigma \sigma_{cc_i} b_i t_i}{b_i t_i} = \frac{\sigma_{cc_1} b_1 t_1 + \sigma_{cc_2} b_2 t_2 + \sigma_{cc_3} b_3 t_3}{b_1 t_1 + b_2 t_2 + b_3 t_3}$$

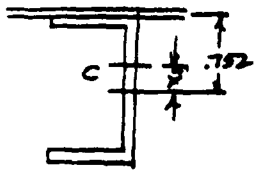
$$= \frac{(2)(29\,000)(.69)(.06) + (32000)(1.32)(.06)}{(2)(.69)(.06) + (1.32)(.06)}$$

$$= 30467 \text{ psi}$$

A TRIAL SOLUTION WILL BE USED TO FIND THE CRIPPLING STRESS INCLUDIN THE EFFECT OF SKIN. NOTE THAT THE EFFECTIVE SKIN WIDTH IS A FUNCTION OF THE COLUMN STRESS σ_c AND THE EFFECTIVE SKIN WIDTH IS NEEDED TO CALCULATE ρ FOR COLUMN EQUATION.

EQUATION FOR EFFECTIVE SKIN WIDTH : $w = .60t\sqrt{\frac{E}{\sigma_c}}$

EQUATION FOR THE COLUMN STRESS : $\sigma_c = \sigma_{cc}\left[1 - \frac{\sigma_{cc}(L'/\rho)^2}{4\pi^2 E}\right]$



$A = .1692\ in^2$
$I = .0544\ in^4$

ASSUME $\sigma_c = 35000$ psi

$$w = (.60)(.063)\sqrt{\frac{10.3\times10^6}{35000}} = .648$$

EFFECTIVE SKIN AREA: $A_s = (2)(.648)(.063) = .082\ in^2$

CENTROIDAL DISTANCE $\bar{y}$

$$\bar{y} = \frac{(.082)(.752)}{.1692+.082} = .245\ in$$

MOMENT OF INERTIA OF ENTIRE AREA ABOUT THE CENTROIDAL AXIS

$$I_c = .0544 + (.082)(.752)^2 - (.1692 + .082)(.245)^2$$
$$= .086\ in^4$$

RADIUS OF GYRATION ABOUT CENTROIDAL AXIS

$$\rho = \sqrt{\frac{I_c}{A_t}} = \sqrt{\frac{.086}{(.1692+.082)}} = .584\ in$$

NOTE: FROM SECTION 2.3 $\longrightarrow L' = 14.16$

CALCULATING COLUMN STRESS:

$$\sigma_c = 30467\left[1 - \frac{30467\,(14.16/.584)^2}{(4)(\pi)^2(10.3\times10^6)}\right]$$
$$= 29125\ psi$$

RECALCULATING w:
(EFFECTIVE SKIN WIDTH)

$$w = (.60)(.063)\sqrt{\frac{10.3\times10^6}{29125}} = .711\ in$$

$$A_s = (2)(.711)(.063) = 0.0896\ in^2$$

$$\bar{y} = \frac{(.0896)(.752)}{.1692 + .0896} = .2603\ in$$

$$I_c = .0544 + (.0896)(.752)^2 - (.1692 + .0896)(.2603)^2$$
$$= .0875 \text{ in}^4$$

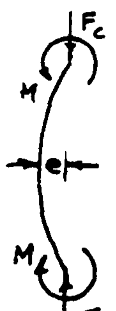
$$\rho = \sqrt{\frac{I_c}{A_t}} = \sqrt{\frac{.0875}{(.1692+.0896)}} = .581 \text{ in}$$

$$\sigma_c = 30467\left[1 - \frac{30467\left(\frac{14.16}{.581}\right)^2}{(4)(\pi)^2(10.3\times10^6)}\right] = 29111 \text{ psi}$$

NOTE: RADIUS OF GYRATION WILL NOT CHANGE THAT MUCH UPON RECALCULATION, THEREFORE COLUMN STRESS IS

$$\sigma_c = 29111 \text{ psi}$$

NOTE: COLUMN Y233.700 IS CURVED AND ALSO HAS A DISTRIBUTED MOMENT M = 1475 in-lb APPLIED TO IT. THE EFFECTIVE ECCENTRICITY AS CALCULATED IN THE BUCKLING ANALYSIS WILL BE CONSIDERED.

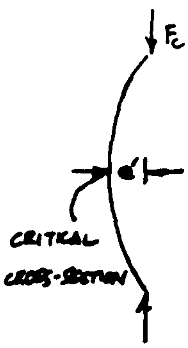


$$e' = e - \frac{M}{F_c}$$

e' = EFFECTIVE ECCENTRICITY

e = CALCULATED ECCENTRICITY

STRESS AT THE CRITICAL CROSS-SECTION CANNOT EXCEED THE COLUMN STRESS σ_c OTHERWISE FAILURE WOULD OCCUR.



$$\sigma_c = \frac{(F_c e')(c)}{I_c} + \frac{F_c}{A_t} = \frac{F_c\left[e - \frac{M}{F_c}\right]c}{I_c} + \frac{F_c}{A_t}$$

AS CALCULATED ABOVE:

$I_c = .0875 \text{ in}^4$

$A_t = .1692 + (2)(.711)(.063) = .2588$

$e = 1.66$ in

$c = .71 + \bar{y} = 0.970$ in

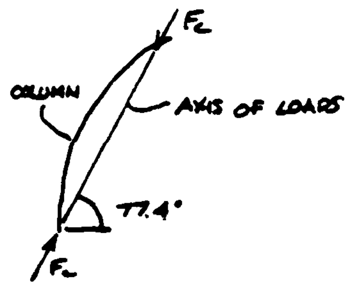
$M = 1475$ in-lb

CALCULATING MAXIMUM ALLOWABLE CRIPPLING LOAD

$$29111 = \frac{[(F_C)(1.66) - 1475](.970)}{.0875} + \frac{F_C}{.2588}$$

$$F_C = 2042 \text{ lb}$$

CALCULATING MAXIMUM ALLOWABLE VERTICAL LOAD FOR CRIPPLING FAILURE. NOTE THAT "F_C" IS ALONG THE "AXIS OF LOADS" AS SHOWN IN SECTION 2.2.



MAXIMUM VERTICAL LOAD = R

$$R = F_C \sin 77.4°$$
$$= 2042 \sin 77.4°$$
$$= 1992 \text{ lb}$$

CALCULATING MAXIMUM ALLOWABLE BIRDSTRIKE

$$1.225\omega = R$$

$$\omega = \frac{1992}{1.225} = 1627 \text{ lb}$$

$$P_{max} = \frac{3.99\omega}{\cos 13°} = \frac{(3.99)(1627)}{\cos 13°} = \underline{\underline{6660}} \quad \left(\text{MAXIMUM BIRDSTRIKE}\right)$$

II. COLUMN Y240.200

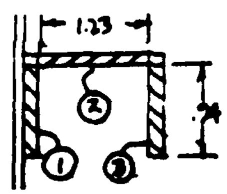


PLATE ① AND ③ — BOTH ENDS AND ONE SIDE SIMPLY SUPPORTED
ONE SIDE FREE.

PLATE ② — BOTH ENDS, BOTH SIDES SIMPLY SUPPORTED

CALCULATING ALLOWABLE CRIPPLING STRESS

PLATES ① AND ③ $\qquad \frac{a}{b} = \frac{1.23}{.94} = 1.31 \implies K_1 = K_3 = 0.905$

PLATE ①: $\qquad \frac{\pi}{\sqrt{K_1}} \frac{b}{t} = \frac{\pi}{\sqrt{.905}} \left(\frac{.94}{.07}\right) = 44.3 \implies \sigma_{cc_1} = 30\,000 \text{ psi}$

PLATE ③: $\qquad \frac{\pi}{\sqrt{K_3}} \frac{b}{t} = \frac{\pi}{\sqrt{.905}} \left(\frac{.94}{.08}\right) = 38.8 \implies \sigma_{cc_3} = 32\,000 \text{ psi}$

PLATE ②: $\frac{a}{b} = \frac{1.23}{1.23} = 1.0 \implies K_2 = 3.62$

$$\frac{\pi}{\sqrt{K_2}}\frac{b}{t} = \frac{\pi}{\sqrt{3.62}}\left(\frac{1.23}{.06}\right) = 33.8 \longrightarrow \sigma_{cc_2} = 33000 \text{ psi}$$

CALCULATING TOTAL CRIPPLING STRESS

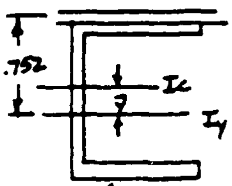
$$\sigma_{cc} = \frac{\Sigma \sigma_{cc_i} b_i t_i}{\Sigma b_i t_i} = \frac{\sigma_{cc_1} b_1 t_1 + \sigma_{cc_2} b_2 t_2 + \sigma_{cc_3} b_3 t_3}{b_1 t_1 + b_2 t_2 + b_3 t_3}$$

$$= \frac{(30000)(.94)(.07) + (33000)(1.23)(.06) + (32000)(.94)(.08)}{(.94)(.07) + (1.23)(.06) + (.94)(.08)}$$

$$= 31731 \text{ psi}$$

THE SAME PROCEDURE WILL BE FOLLOWED TO FIND THE MAXIMUM ALLOWABLE BIRDSTRIKE LOAD FOR CRIPPLING FAILURE OF COLUMN Y240.200

ASSUME $\sigma_c = 30\,000$ psi $\longrightarrow$ $w = (.6)(.063)\sqrt{\frac{10.3 \times 10^6}{30000}} = .70$



A = .2238 in²

$I_y = .0731$ in⁴

EFFECTIVE SKIN AREA: $(2)(.70)(.063) = .088 \text{ in}^2$

CENTROIDAL DISTANCE $\bar{y}$: $\bar{y} = \frac{(.088)(.752)}{.2238 + .088} = .212$ in

MOMENT OF INERTIA ABOUT CENTROIDAL AXIS

$$I_c = .0731 + (.088)(.752)^2 - (.2238 + .088)(.212)^2$$
$$= .1360 \text{ in}^4$$

RADIUS OF GYRATION $\quad \rho = \sqrt{\frac{I_c}{A_c}} = \sqrt{\frac{.1369}{(.2238 + .088)}} = .663$ in

PINNED / PINNED CONDITION: $L' = 22.79$ in

FIXED / PINNED CONDITION: $L' = 15.95$ in

COLUMN STRESS $\quad \sigma_c = 31731\left[1 - \frac{31731\left(\frac{22.79}{.663}\right)^2}{(4)(\pi)^2(10.3 \times 10^6)}\right]$ (PINNED/PINNED) $= 28805$ p

$$\sigma_c = 31731\left[1 - \frac{31731\left(15.95/.663\right)^2}{(4)(\pi)^2(10.3 \times 10^6)}\right]$$ (FIXED/PINNED) $= 30298$ p

A. RECALCULATING ω — FOR PINNED/PINNED CONDITION

$$\omega = (.6)(.063)\sqrt{\frac{10.3\times10^6}{28305}} = 0.715$$

$$A_s = (2)(.715)(.063) = 0.0901 \text{ in}^2$$

$$\bar{Y} = \frac{(.0901)(.752)}{.2238+.0901} = 0.216 \text{ in}$$

$$I_c = .0731 + (.0901)(.752)^2 - (.2238+.0901)(.216)^2$$
$$= 0.1094$$

$$\rho = \sqrt{\frac{I_c}{A_t}} = \sqrt{\frac{0.1094}{(.0901+.2238)}} = 0.590 \text{ in}$$

$$\sigma_c = 31731\left[1 - \frac{31731\left(\frac{22.79}{.590}\right)^2}{(4)(\pi)^2(10.3\times10^6)}\right] = 28036$$

$$\omega = (.6)(.063)\sqrt{\frac{10.3\times10^6}{28036}} = 0.724 \text{ in}$$

$$A_s = (2)(.724)(.063) = .0913 \text{ in}^2$$

$$\bar{Y} = \frac{(.0913)(.752)}{.2238+.0913} = 0.218 \text{ in}$$

$$I_c = .0731 + (.0913)(.752)^2 - (.218)^2(.2238+.0913)$$
$$= 0.1098 \text{ in}^4$$

$$\rho = \sqrt{\frac{0.1098}{(.2238+.0913)}} = 0.590$$

<u>NOTE</u>: ρ DID NOT CHANGE SIGNIFICANTLY THEREFORE $\sigma_c = 28036$ psi

B. RECALCULATING ω — FOR FIXED/PINNED CONDITION

$$\omega = (.6)(.063)\sqrt{\frac{10.3\times10^6}{30298}} = 0.697 \text{ in}$$

$$A_s = (2)(.697)(.063) = 0.0878 \text{ in}^2$$

$$\bar{Y} = \frac{(.0878)(.752)}{.2238+.0878} = 0.212 \text{ in}$$

$$I_c = .0731 + (.0878)(.752)^2 - (.2238+.0878)(.212)^2$$
$$= 0.109 \text{ in}^4$$

$$\rho = \sqrt{\frac{.109}{(.0878+.2238)}} = 0.591$$

$$\sigma_c = 25520\left[1 - \frac{25520\left(\frac{15.35}{.589}\right)^2}{(4)(\pi)^2(10.3\times10^6)}\right] = 24346 \text{ psi}$$

$$w = (.6)(.063)\sqrt{\frac{10.3\times10^6}{24346}} = .778 \text{ in}$$

$$A_s = (2)(.778)(.063) = .098 \text{ in}^2$$

$$\bar{y} = \frac{(.098)(.752)}{.2238 + .098} = .229 \text{ in}$$

$$I_c = .0731 + (.098)(.752)^2 - (.2238 + .098)(.229)^2$$
$$= .112 \text{ in}^4$$

$$\rho = \sqrt{\frac{.112}{(.098 + .2238)}} = .589$$

THEREFORE $\sigma_c = 24346$ psi FOR FIXED/PINNED CONDITION
(ρ DID NOT CHANGE SIGNIFICANTLY)

CALCULATING MAXIMUM ALLOWABLE CRIPPLING LOADS

A. FOR PINNED/PINNED CONDITION

$$\sigma_c = \frac{F_c\left[e - \frac{M}{F_c}\right]c}{I_c} + \frac{F_c}{A_t}$$

$I_c = .1112 \text{ in}^4$ $\quad A_t = .2238 + .101 = .325 \text{ in}^2$

$e = 1.71 \text{ in}$ $\quad c = .66 + .233 = .893 \text{ in}$

$M = 4525 \text{ in·lb}$ $\quad \sigma_c = 23122 \text{ psi}$

$$23122 = \frac{F_c\left[1.71 - \left(\frac{4525}{F_c}\right)\right](.893)}{.1112} + \frac{F_c}{.325}$$

$F_c = 3537 \text{ lb}$

B. FOR FIXED/PINNED CONDITION

$I_c = .112 \text{ in}^4$ $\quad A_t = .2238 + .098 = .322 \text{ in}^2$

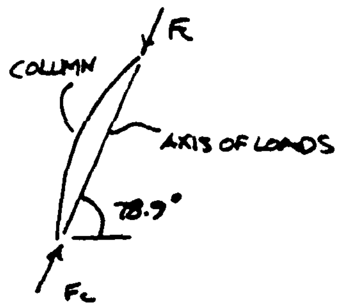
$e = 1.71 \text{ in}$ $\quad c = .66 + .229 = .889 \text{ in}$

$M = 4525 \text{ in·lb}$ $\quad \sigma_c = 24346 \text{ psi}$

$$24346 = \frac{F_c\left[1.71 - \left(\frac{4525}{F_c}\right)\right](.889)}{.112} + \frac{F_c}{.322}$$

$F_c = 3613 \text{ lb}$

CALCULATING MAXIMUM ALLOWABLE VERTICAL LOAD FOR CRIPPLING



A. FOR PINNED/PINNED CONDITION

$$R = F_c \sin 78.9° = 3812 \sin 78.9° = 3741 \text{ lb}$$

B. FOR FIXED/PINNED CONDITION

$$R = F_c \sin 78.9° = 3915 \sin 78.9° = 3842 \text{ lb}$$

CALCULATING MAXIMUM BIRDSTRIKE LOAD FOR CRIPPLING

A. PINNED/PINNED CONDITION

$$2.765 w = R$$

$$w = \frac{3741}{2.765} = 1353 \text{ lb/in} \qquad P_{max} = \frac{3.99 w}{\cos 13°} = \frac{(3.99)(1353)}{\cos 13°} = \underline{\underline{5540 \text{ lb}}}$$

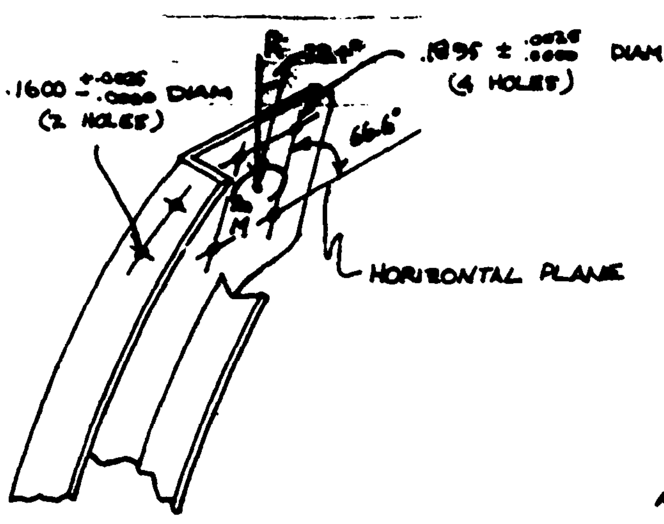
B. FIXED/PINNED CONDITION

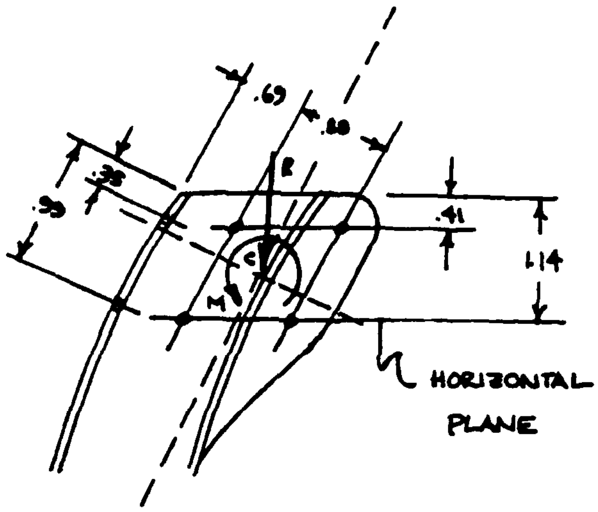
$$2.765 w = R$$

$$w = \frac{3842}{2.765} = 1389 \text{ lb/in} \qquad P_{max} = \frac{(3.99)(1389)}{\cos 13°} = \underline{\underline{5690 \text{ lb}}}$$

ANALYSIS
OF
FASTENERS
AT
Y233.700
AND
Y240.200

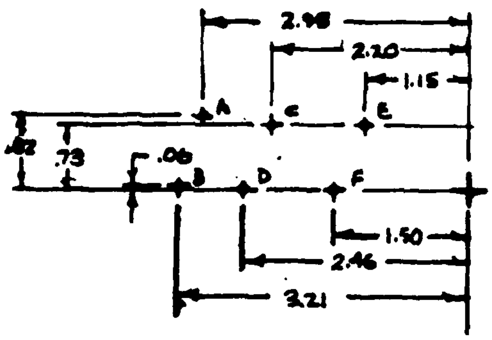
SHEAR STRESS ANALYSIS - Section 4.1.1 Fasteners at Column Y233.700





ASSUME R ACTS THROUGH CENTROID

RIB AT Y233.700



TO FIND CENTROID OF THE HOLES

$$\bar{x} = \frac{\sum_{1}^{n} A_i x_i}{\sum_{1}^{n} A_i} \qquad \bar{y} = \frac{\sum_{1}^{n} A_i y_i}{\sum_{1}^{n} A_i}$$

A_i = CROSS-SECTIONAL AREA OF BOLT "i"
x_i = x DISTANCE TO A_i
y_i = y DISTANCE TO A_i
$\bar{x}$ = x DISTANCE TO CENTROID
$\bar{y}$ = y DISTANCE TO CENTROID

NOTE: $A_A = A_B = (.16)^2\left(\frac{\pi}{4}\right) = .020 \text{ in}^2$
$A_C = A_D = A_E = A_F = (.1895)^2\left(\frac{\pi}{4}\right) = .028 \text{ in}^2$

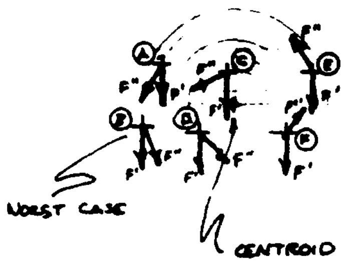
$$\bar{x} = \frac{(A_A)(2.95) + (A_B)(3.21) + (A_C)(2.20) + (A_D)(2.46) + (A_E)(1.15) + (A_F)(1.50)}{A_A + A_B + A_C + A_D + A_E + A_F}$$

$\bar{x} = 2.16$ in

$$\bar{y} = \frac{(A_A)(.82) + (A_B)(.06) + (A_C)(.73) + (A_E)(.73)}{A_A + A_B + A_C + A_D + A_E + A_F}$$

NOTE: $(A_D)(0) = 0$
$(A_F)(0) = 0$

$\bar{y} = .38$ in



F'' - LOAD DUE TO BENDING MOMENT OF ARCH

F' - VERTICAL SHEAR AT EACH BOLT

RADIAL DISTANCES FROM CENTROID TO THE CENTER OF EACH BOLT

$$d_A = \sqrt{(2.95-2.16)^2+(.82-.38)^2} = .90 \text{ in}$$
$$d_B = \sqrt{(3.21-2.16)^2+(.06-.38)^2} = 1.10 \text{ in}$$
$$d_C = \sqrt{(2.20-2.16)^2+(.73-.38)^2} = .35 \text{ in}$$
$$d_D = \sqrt{(2.46-2.16)^2+(.38)^2} = .48 \text{ in}$$
$$d_E = \sqrt{(1.15-2.16)^2+(.72-.38)^2} = 1.07 \text{ in}$$
$$d_F = \sqrt{(1.40-2.16)^2+(.38)^2} = .76 \text{ in}$$

ANALYZING THE WORST CASE: BOLT AT POINT "B" BOLT IS AT FURTHEST DISTANCE AND HAS THE SMALLEST CROSS-SECTIONAL AREA.

CROSS-SECTIONAL AREA = .020 in

DISTANCE FROM CENTROID = $d_B = 1.10$ in

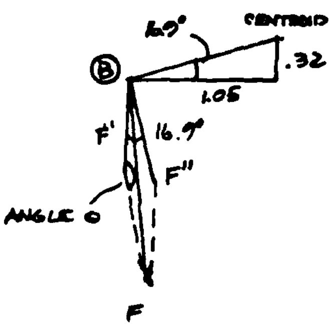
$$F_B' = \frac{R}{n} = \frac{R}{6}$$

R = MAXIMUM VERTICAL FORCE DUE TO BIRDSTRIKE

n = NUMBER OF BOLTS

$$F_B'' = \frac{M d_B}{d_A^2+d_B^2+d_C^2+d_D^2+d_E^2+d_F^2}$$
$$= \frac{(1475)(1.10)}{(.90)^2+(1.1)^2+(.35)^2+(.48)^2+(1.07)^2+(.76)^2}$$
$$= 396 \text{ lb}$$

M = ARCH MOMENT EQUAL TO THE DISTRIBUTED MOMENT AT Y233.700 (M = 1475 in·lb



F_B = MAXIMUM ALLOWABLE SHEAR FORCE IN BOLT B

NOTE: BOLT B HAS THE FOLLOWING SPECIFICATIONS:

- $\frac{5}{32}$" LOCK BOLT
- TITANIUM 6AL-4V NAS 621
- MAXIMUM ALLOWABLE SHEAR FORCE = 4000 lb

USE LAW OF COSINES TO FIND F' (VERTICAL SHEAR)

$$(F_B)^2 = (F_B')^2 + (F_B'')^2 - 2F_B'F_B'' \cos\theta$$
$$(4000)^2 = (F_B')^2 + (396)^2 - (2)(F_B')(396)\cos 163.1°$$
$$(F_B')^2 + 758 F_B' - 15\,843\,184 = 0$$

SOLVING USING QUADRATIC FORMULA

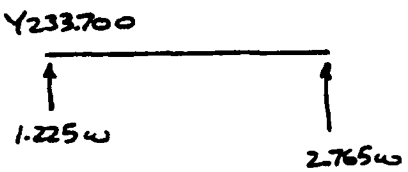
$$F_B' = \frac{-758 \pm \sqrt{(758)^2 - (4)(-15\,863\,184)}}{2}$$

$F_B' = 3619$ lb (NOTE: THE OTHER ROOT IS EXTRANEOUS)

CALCULATING MAXIMUM VERTICAL FORCE DUE TO BIRDSTRIKE (R)

$$R = nF_B' = (6)(3619) = 21\,715 \text{ lb}$$

CALCULATING MAXIMUM BIRDSTRIKE LOAD



$$1.225\,w = R$$

$$w = \frac{21\,715}{1.225} = 17\,727 \text{ lb}$$

$$P_{max} = \frac{3.99\,w}{\cos 13^\circ} = \frac{(3.99)(17\,727)}{\cos 13^\circ} = \underline{\underline{72\,593 \text{ lb}}}$$ (MAXIMUM BIRDSTRIKE

BEARING LOAD ANALYSIS - Column Y233.700

COLUMNS Y233.700 AND Y240.200 ARE MADE OF 7075-T7351

F_{bru} ($e/D = 1.5$) = 106 ksi $\quad$ F_{bry} ($e/D = 1.5$) = 86 ksi

F_{bru} ($e/D = 2.0$) = 137 ksi $\quad$ F_{bry} ($e/D = 2.0$) = 104 ksi

I FOR COLUMN Y233.700 - WORST WILL BE AT BOLT B. THEREFORE THE BEARING LOAD FOR *ULTIMATE FAILURE* WILL BE **ANALYZED** AT THIS POINT ON THE COLUMN

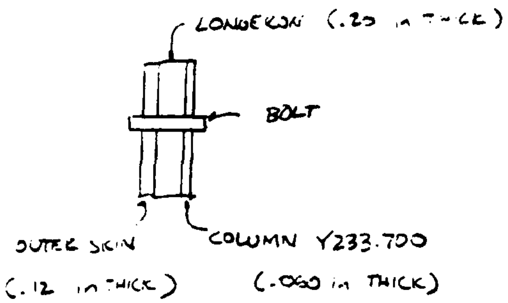
F_b = BEARING LOAD

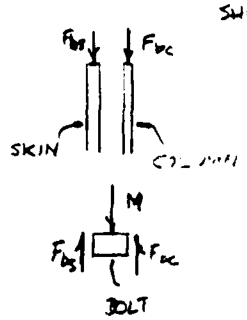
t = THICKNESS

d = DIAMETER = .1563 in

$$\sigma_b = \frac{F_b}{td}$$

FOR BEARING STRESS ON OUTER SKIN AND COLUMN, NOTE THAT BOLT IS IN DOUBLE SHEAR





$$F_{bs} + F_{bc} = M$$

$$\sigma_{bs} t_s d + \sigma_{bc} t_c d = M$$

σ_{bs} = BEARING STRESS OF SKIN

σ_{bc} BEARING STRESS OF COLUMN

t_s = THICKNESS OF SKIN

t_c = THICKNESS OF COLUMN

BEARING STRESS CAN BE FOUND BY INTERPOLATION. NOTE THAT THE SKIN AND THE COLUMN ARE MADE OF SAME MATERIAL 7075-T7351.

FOR σ_{bs}: $\quad \frac{e}{d} = \frac{t}{d} = \frac{.12}{.1563} = .768 \longrightarrow \sigma_{bs} = 60\,620$ psi

FOR σ_{bc}: $\quad \frac{e}{d} = \frac{t}{d} = \frac{.06}{.1563} = .384 \longrightarrow \sigma_{bc} = 36\,800$ psi

CALCULATING MAXIMUM ALLOWABLE BEARING LOAD

$$\sigma_{bs} t_s d + \sigma_{bc} t_c d = F_{MB}$$

$$(60620)(.12)(.1563) + (36800)(.06)(.1563) = F_{MB}$$

$$F_{MB} = 1482 \text{ lb}$$

NOTE: F_{MB} = MAXIMUM ALLOWABLE BEARING LOAD AT BOLT (B)

USE LAW OF COSINES TO FIND MAXIMUM ALLOWABLE VERTICAL LOAD (R)

$$(F_{MB})^2 = (F_B')^2 + (F_B'')^2 - 2F_B'F_B''\cos\theta$$

AS PREVIOUSLY CALCULATED $F_B'' = 396$

$\theta = 163.1°$

$$(1482)^2 = (F_B')^2 + (396)^2 - (2)(F_B')(396)\cos 163.1°$$

$$(F_B')^2 + 758F_B' - 2\,039\,508 = 0$$

$$F_B' = \frac{-758 \pm \sqrt{(758)^2 - (4)(-2039508)}}{2}$$

$$F_B' = 1100 \text{ lb}$$

R = MAXIMUM ALLOWABLE VERTICAL LOAD AT COLUMN Y233.700

$$R = nF_B' = (6)(1100) = 6600 \text{ lb}$$

CALCULATING MAXIMUM BIRDSTRIKE LOAD:

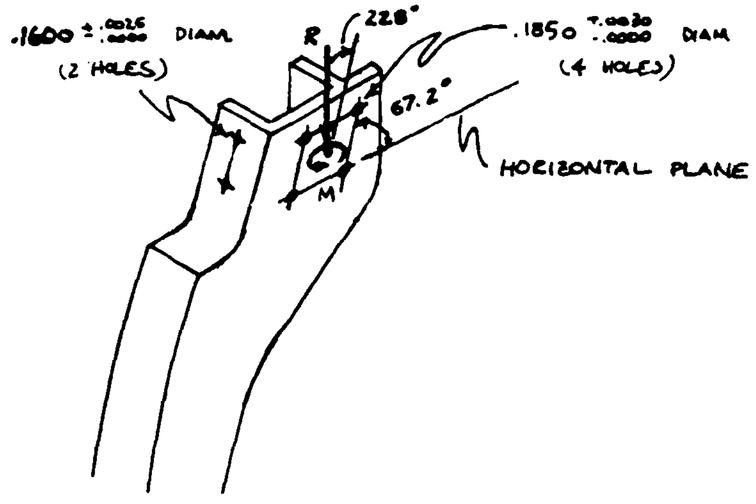
$$1.225\,w = R$$

$$w = \frac{6600}{1.225} = 5388$$

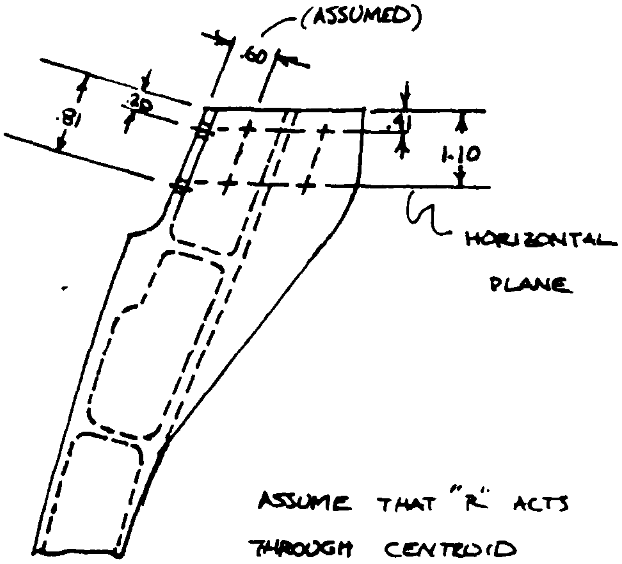
$$P_{MAX} = \frac{3.99w}{\cos 13°} = \frac{(3.99)(5388)}{\cos 13°} = \underline{\underline{22\,063 \text{ lb}}}$$ (MAXIMUM BIRDSTRIK

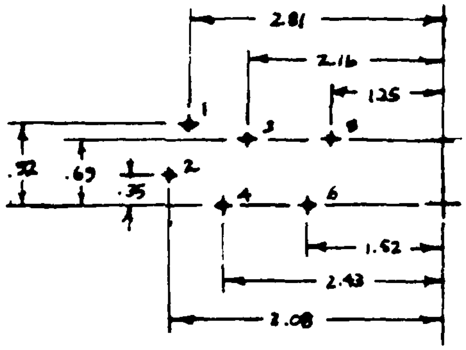
Section 4.3.1

SHEAR STRESS ANALYSIS - Fasteners at Column Y240.200



RIB AT Y240.200





$A_1 = A_2 = (.16)^2(\frac{\pi}{4}) = .020 \text{ in}^2$

$A_3 = A_4 = A_5 = A_6 = (.1850)^2(\frac{\pi}{4}) = .027 \text{ in}^2$

$$\bar{x} = \frac{(A)(2.81) + (A_2)(3.08) + (A_3)(2.16) + (A_4)(2.43) + (A_5)(1.25) + (A_6)(1.52)}{A_1 + A_2 + A_3 + A_4 + A_5 + A_6}$$

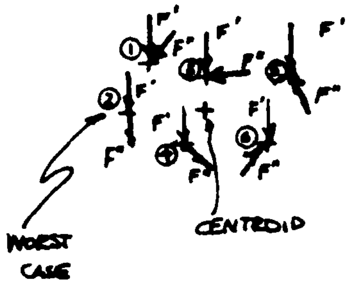
$$\bar{y} = \frac{(A_1)(.92) + (A_2)(.35) + (A_3)(.69) + (A_5)(.69)}{A_1 + A_2 + A_3 + A_4 + A_5 + A_6}$$

NOTE: $(A_4)(0) = 0$
$(A_6)(0) = 0$

$\bar{x} = 2.14 \text{ in}$

$\bar{y} = 0.42 \text{ in}$

ASSUME THAT THE VERTICAL FORCE "R" AND THE ARCH MOMENT "M" ACT THROUGH THE CENTROID.



F" = LOAD DUE BENDING MOMENT OF ARCH.

F' = VERTICAL SHEAR AT EACH BOLT / DISTRIBUTED EQUALLY

NEED TO FIND RADIAL DISTANCES FROM CENTROID TO THE CENTER OF EACH BOLT

$$d_1 = \sqrt{(2.81-2.14)^2+(.92-.42)^2} = .84 \text{ in}$$
$$d_2 = \sqrt{(3.08-2.14)^2+(.35-.42)^2} = .94 \text{ in}$$
$$d_3 = \sqrt{(2.16-2.14)^2+(.69-.42)^2} = .27 \text{ in}$$
$$d_4 = \sqrt{(2.43-2.14)^2+(0-.42)^2} = .51 \text{ in}$$
$$d_5 = \sqrt{(1.25-2.14)^2+(.69-.42)^2} = .93 \text{ in}$$
$$d_6 = \sqrt{(1.52-2.14)^2+(0-.42)^2} = .75 \text{ in}$$

ANALYZING THE WORST CASE — BOLT AT POINT (2) FURTHEST DISTANCE AND SMALLEST CROSS-SECTION

CROSS-SECTIONAL AREA OF BOLT = .020 in^2

DISTANCE FROM CENTROID d_2 = .94 in

$$F_2' = \frac{R}{n} = \frac{R}{6}$$

R = MAXIMUM VERTICAL FORCE DUE TO BIRDSTRIKE

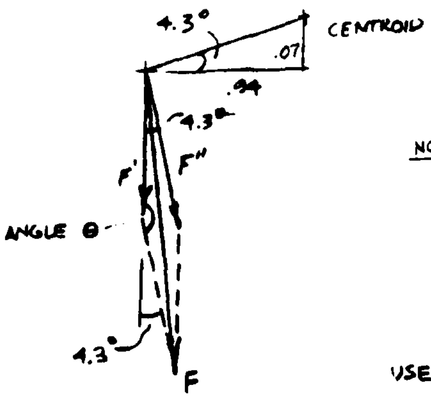
n = NUMBER OF BOLTS

$$F_2'' = \frac{M d_2}{d_1^2+d_2^2+d_3^2+d_4^2+d_5^2+d_6^2}$$

M = ARCH MOMENT, EQUAL TO DISTRIBUTED MOMENT AT Y240.200 (M = 4525 -

$$= \frac{(4525)(.94)}{(.84)^2+(.94)^2+(.27)^2+(.51)^2+(.93)^2+(.75)^2}$$

$$= 1270 \text{ lb}$$



F_2 = MAXIMUM ALLOWABLE SHEAR FORCE IN BOLT (2)

NOTE: BOLT (2) HAS THE FOLLOWING SPECIFICATION:

- $\frac{5}{32}$" LOCK BOLT
- TITANIUM 6AL-4V NAS 621
- MAXIMUM ALLOWABLE SHEAR FORCE = 4000 lb

USE LAW OF COSINES TO FIND F' (VERTICAL SHEAR)

$$(F_2)^2 = (F_2')^2 + (F_2'')^2 - 2F'F''\cos\theta$$
$$(4000)^2 = (F_2')^2 + (1270)^2 - (2)(F')(1270)\cos 175.7$$
$$(F_2')^2 + 2533\,F' - 14\,387\,100 = 0$$

SOLVING USING QUADRATIC FORMULA

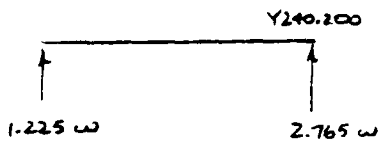
$$F_2' = \frac{-2533 \pm \sqrt{(2533)^2 - (4)(-14\,387\,100)}}{2}$$

$F_2' = 2732$ lb (NOTE: OTHER ROOT IS EXTRANEOUS)

CALCULATING MAXIMUM VERTICAL FORCE DUE TO BIRDSTRIKE (R)

$$R = nF_2' = 6(2732) = 16\,392 \text{ lb}$$

CALCULATING MAXIMUM BIRDSTRIKE LOAD



$$2.765\,\omega = R$$

$$\omega = \frac{16392}{2.765} = 5928 \text{ lb}$$

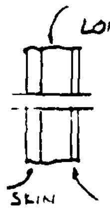
$$P_{MAX} = \frac{3.99\,\omega}{\cos 13^\circ} = \frac{(3.99)(5928)}{\cos 13^\circ} = \underline{\underline{24\,276 \text{ lb}}}$$ (MAXIMUM BIRDSTRIKE

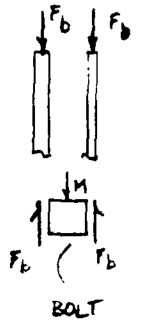
BEARING LOAD ANALYSIS – Column 240.200

FOR COLUMN Y240.200 – WORST CASE WILL BE AT BOLT ② . BEARING LOAD FOR ULTIMATE FAILURE WILL BE ANALYZED.

F_b = BEARING LOAD
t = THICKNESS
d = DIAMETER = .1563 in

$$\sigma_b = \frac{F_b}{td}$$





$$F_b + F_b = F_M$$
$$\sigma_{bs} t_s d + \sigma_{bc} t_c d = F_M$$

σ_{bs} = BEARING STRESS OF SKIN
σ_{bc} = BEARING STRESS OF COLUMN
t_s = SKIN THICKNESS
t_c = COLUMN THICKNESS

BEARING STRESSES ARE FOUND BY INTERPOLATION.

FOR σ_{bs} : $\frac{e}{d} = \frac{t}{d} = \frac{.12}{.1563} = .768 \longrightarrow \sigma_{bs} = 60\,620$ psi

FOR σ_{bc} : $\frac{e}{d} = \frac{t}{d} = \frac{.070}{.1563} = .448 \longrightarrow \sigma_{bc} = 40\,776$ psi

CALCULATING MAXIMUM ALLOWABLE BEARING LOAD

$$\sigma_{bs} t_s d + \sigma_{bc} t_c d = F_{M2}$$
$$(60\,620)(.12)(.1563) + (40\,776)(.07)(.1563) = F_M$$
$$F_{M2} = 1583 \text{ lb}$$

USE LAW OF CO[illegible] TO FIND MAXIMUM ALLOWABLE VERTICAL LOAD (F')

$$(F_{M2})^2 = (F_2')^2 + (F_2'')^2 - 2F_2'F_2''\cos\theta$$

AS PREVIOUSLY CALCULATED $F_2'' = 1270$ lb
$\theta = 175.7°$

$$(F_2')^2 + 2533\,F_2' - 892\,990 = 0$$

$$F_2' = \frac{-2533 \pm \sqrt{(2533)^2 - (4)(-8\ldots9\ldots)}}{2}$$

$F_2' = 315$ lb (NOTE: OTHER ROOT IS EXTRANEOUS)

ANALYZING BEARING LOAD FOR EACH BOLT

CALCULATING LOAD DUE TO BENDING MOMENT FOR EACH BOLT

NOTE $$F_4'' = \frac{M\,d_4}{d_1^2 + d_2^2 + \ldots + d_n^2}$$

$$F_1'' = \frac{(4525)(.84)}{3.35} = 1135 \text{ lb}$$

F_2'' = CALCULATED PREVIOUSLY

$$F_3' = \frac{(4525)(.27)}{3.35} = 365 \text{ lb}$$

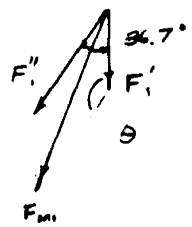
$$F_4' = \frac{(4525)(.51)}{3.35} = 689 \text{ lb}$$

$$F_5' = \frac{(4525)(.93)}{3.35} = 1256 \text{ lb}$$

$$F_6' = \frac{(4525)(.75)}{3.35} = 1013 \text{ lb}$$

MAXIMUM ALLOWABLE VERTICAL LOADS WILL BE ANALYZED IN THE SAME PROCEDURE AS ABOVE.

BOLT 1 : F_{M1} = MAXIMUM ALLOWABLE BEARING LOAD = 1583 lb
(SAME AS F_{M2})



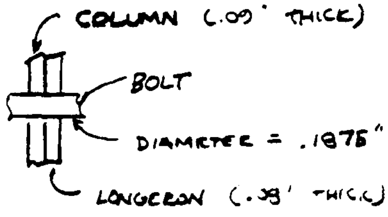
$$(F_{M1})^2 = (F_1')^2 + (F_1'')^2 - 2F_1'F_1''\cos\theta$$

$$(1583)^2 = (F_1')^2 + (1135)^2 - 2(F_1')(1135)\cos 143.3°$$

$$(F_1')^2 + 1820F_1' - 1217664 = 0$$

$$F_1' = 520 \text{ lb}$$

MAXIMUM ALLOWABLE BEARING LOADS FOR BOLTS 3 − 6,



$$\frac{t}{d} = \frac{e}{D} = \frac{.08}{.1875} = .427$$

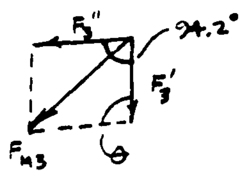
BY LINEAR INTERPOLATION

$$\sigma_b = 39\,475 \text{ psi}$$

MAXIMUM ALLOWABLE BEARING LOAD FOR BOLTS 3−6

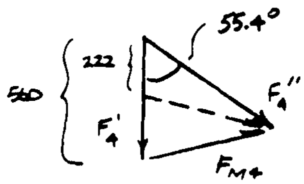
$$F_{M3} = F_{M4} = F_{M5} = F_{M6} = \sigma_b t d$$
$$= (39\,475)(.08)(.1875)$$
$$= 592 \text{ lb}$$

BOLT 3:



$$(F_{M3})^2 = (F_3')^2 + (F_3'')^2 - 2F_3'F_3'' \cos\theta$$
$$(592)^2 = (F_3')^2 + (365)^2 - 2F_3'(365)\cos 94.2^\circ$$
$$(F_3')^2 + 53.5F_3' - 483\,689 = 0$$
$$F_3' = 669 \text{ lb}$$

BOLT 4:



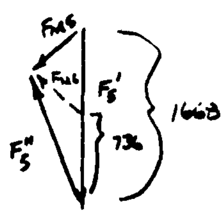
$$(F_{M4})^2 = (F_4')^2 + (F_4'')^2 - 2F_4'F_4'' \cos 55.4^\circ$$
$$(592)^2 = (F_4')^2 + (689)^2 - 2F_4'(689)\cos 55.4^\circ$$
$$(F_4')^2 - 782F_4' + 124\,257 = 0$$

SOLVING THE QUADRATIC EQUATION GIVES TWO ROOTS:

$$F_4' = 560 \text{ lb} \quad \text{or} \quad F_4' = 222 \text{ lb}$$

THE HIGHER VALUE WILL BE TAKEN

BOLT 5:

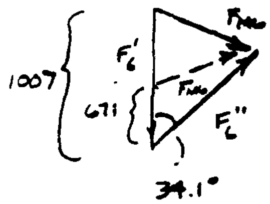


$$(F_{M5})^2 = (F_5')^2 + (F_5'')^2 - 2F_5'F_5'' \cos\theta$$
$$(592)^2 = (F_5')^2 + (1256)^2 - 2F_5'(1256)\cos 16.9^\circ$$

$$F_5' = 1668 \text{ lb} \quad \text{or} \quad F_5' = 736 \text{ lb}$$

AGAIN THE HIGHER VALUE WILL BE TAKEN

BOLT 6:



$$(F_{M6})^2 = (F_6')^2 + (F_6'')^2 - 2F_6'F_6'' \cos 34.1^\circ$$
$$(592)^2 = (F_6')^2 + (1013)^2 - (2F_6')(1013) \cos 34.1^\circ$$

$$F_6' = 1007 \text{ lb} \quad \text{or} \quad F_6 = 671. \text{ lb}$$

CALCULATING MAXIMUM ALLOWABLE VERTICAL LOAD FOR ULTIMATE FAILURE

$$\begin{aligned} R &= F_1' + F_2' + F_3' + F_4' + F_5' + F_6' \\ &= 520 + 315 + 669 + 560 + 1668 + 1007 \\ &= 4739 \text{ lb} \end{aligned}$$

CALCULATING MAXIMUM ALLOWABLE BIRDSTRIKE LOAD

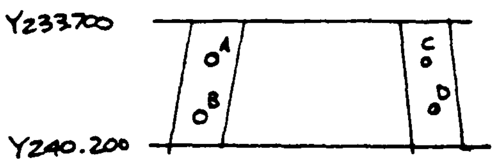
$$2.765\,w = R$$
$$w = \frac{4739}{2.766} = 1714 \ \frac{\text{lb}}{\text{in}}$$

$$P_{max} = \frac{3.99w}{\cos 13^\circ} = \frac{(3.99)(1714)}{\cos 13^\circ} = \underline{\underline{7018 \text{ lb}}}$$ (MAXIMUM BIRDSTRIKE)

FAILURE ANALYSIS OF BOLTS CONNECTING ARCH

SUPPORT WINDSHIELD ATTACH — SHEAR LOAD ANALYSIS ON BOLTS

NOTE: THE FOLLOWING BOLTS ARE USED TO ATTACH THE ARCH TO THE UPPERLONGERON.



BOLTS USED FOR HOLES "B" AND "D" ARE THE SAME

ST3M454 → DESIGNED FOR HIGH SHEAR STRESS AND MODERATE LOADS

TENSILE STRENGTH: $S_U = 205{,}000$ psi

YIELD STRENGTH: $S_y = 190{,}000$ psi

BOLT USED FOR HOLE "C"

ST3M731 -4-19

TENSILE STRENGTH: $S_U = 130{,}000$ psi

YIELD STRENGTH: $S_y = 120{,}000$ psi

MODULUS: $E = 16 \times 10^6$ psi

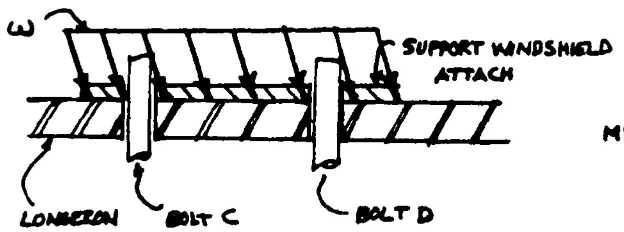
BOLT USED FOR HOLE "A" CAN BE ONE OF THE FOLLOWING

4140 MS 5626   8740 MS 1649

4340 MS 5000   6150 MS 8503

8735 MS 1698

I. SHEAR ANALYSIS ON BOLTS "C" AND "D" USING DISTORTION-ENERGY THEORY: $(\tau_{max} = .577\, S_y)$



$\omega = \dfrac{\text{LOAD } (P_{max})}{\text{UNIT LENGTH}}$

$\tau_{yc} = (120000)(.577) = 69\,240$ psi

$\tau_{yD} = (190000)(.577) = 109\,630$ psi

MAXIMUM SHEAR IN BOLTS

$F_{S_c(max)} = \tau_{yc} A_c = (69\,240)(\frac{\pi}{4})(\frac{1}{4})^2$

$= 3400$ lb

$F_{S_D(max)} = \tau_{yD} A_D = (109\,630)(\frac{\pi}{4})(\frac{5}{16})^2$

$= 8410$ lb

CALCULATING "P_{max}" WE WILL CONSIDER THE SMALLER SHEAR FORCE AND USE THIS AS OUR FAILURE PT. NOTE THAT THERE ARE 2 BOLTS THEREFORE THIS VALUE WILL BE MULTIPLIED BY TWO.

$$(P_{max}) \sin 13° = (2)(F_{s_{c(max)}}) = (2)(3400)$$

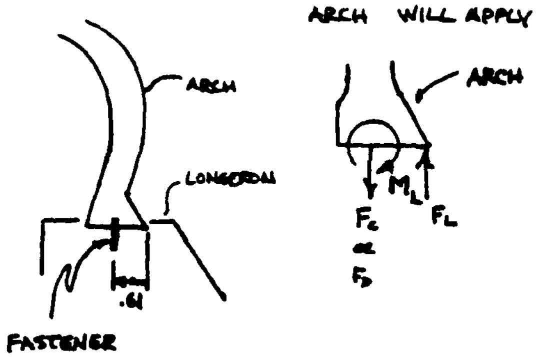
$$P_{max} = \frac{(3400)(2)}{\sin 13°}$$

$$P_{max} = \underline{30\,228 \text{ lb}} \quad \text{(MAXIMUM BIRDSTRIKE)}$$

$$\omega = P/\ell = \frac{30228}{3.99} = 7575 \text{ lb/in}$$

II. MAXIMUM ALLOWABLE BENDING MOMENT FROM ARCH TO FAIL BOLTS THAT ATTACH ARCH TO LONGERON

ARCH WILL APPLY A MOMENT TO LONGERON. CONSIDER THE COUPLE AT THE FOOT OF THE ARCH.



F_L = REACTIVE FORCE OF THE LONGERON TO FOOT OF ARCH.

F_c = TENSILE FORCE OF BOLT C

F_D = TENSILE FORCE OF BOLT D

M_L = MOMENT APPLIED TO LONGERON

FOR BOLT C :

$$M_{L_c} = (F_c)(.61) = (\sigma_c A_c)(.61)$$

NOTE: $F_c = \sigma_c A_c$

σ_c = TENSILE STRESS OF BOLT C = 130 000 psi

A_c = CROSS-SECTIONAL AREA.

$$M_{L_c} = (130000)\left(\frac{\pi}{4}\right)\left(\frac{1}{4}\right)^2(.61) = 3893 \text{ lb}\cdot\text{in}$$

FOR BOLT D:

$$M_{L_D} = (F_D)(.61) = (205000)\left(\frac{\pi}{4}\right)\left(\frac{5}{16}\right)^2(.61) = 9590 \text{ lb}\cdot\text{in}$$

MAXIMUM ALLOWABLE MOMENT SUPPLIED BY THE ARCH — BOLT "C" WILL FAIL FIRST THEREFORE

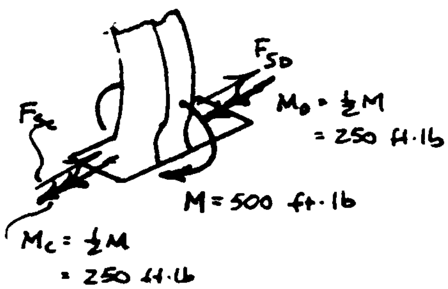
$$M_{max} = (2)(3893) = 7786 \text{ lb}\cdot\text{in}$$

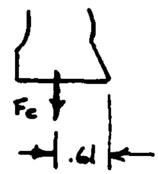
$$M_{max} = (7786 \text{ lb}\cdot\text{in})\left(\frac{1 \text{ ft}}{12 \text{ in}}\right) = \underline{649 \text{ ft}\cdot\text{lb}}$$

III. CALCULATING MAXIMUM ALLOWABLE BIRDSTRIKE LOAD TO CAUSE FAILURE IN THE WINDSHIELD ATTACH FASTENERS.

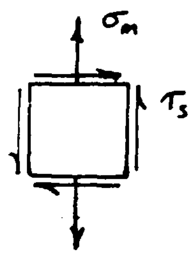
NOTE: A 500 ft·lb (6000 in-lb) MOMENT WILL BE APPLIED TO THE UPPER LONGERON. THIS ANALYSIS WILL CONSIDER THE COMBINED EFFECT OF THE ARCH MOMENT AND SHEAR FORCE ON FASTENERS "C" AND "D".

BOTH BOLTS "C" AND "D" PRODUCE A COUPLE TO COUNTERACT THE BENDING MOMENT PRODUCED FROM THE ARCH. THE BENDING MOMENT WILL BE ASSUMED TO BE EQUALLY DISTRIBUTED TO BOLT "C" AND "D".





BOLT "C" WILL FAIL FIRST: DIAMETER = .25 in
TENSILE STRENGTH = 130 000 psi



σ_M = TENSILE STRESS DUE TO BENDING MOMENT
τ_s = SHEAR STRESS DUE TO BIRDSTRIKE.

$$\sigma_m = \frac{F_c}{A_c} = \frac{\left(\frac{M_c}{.61}\right)}{A_c} = \frac{(3000/.61)}{(\frac{\pi}{4})(.25)^2} = 100\,190 \text{ psi}$$

$$\tau_s = \frac{F_{sc}}{A_c} = \frac{(P_{max})(\sin 13°)}{(\frac{\pi}{4})(.25)^2} = 4.583\, P_{max}$$

APPLYING MOHR'S CIRCLE CRITERIA

$$\sigma_{max} = \left(\frac{\sigma_m}{2}\right) + \sqrt{\left(\frac{\sigma_m}{2}\right)^2 + (\tau_s)^2}$$

$$130\,000 = \frac{100\,190}{2} + \sqrt{\left(\frac{100\,190}{2}\right)^2 + (4.583\, P_{max})^2}$$

$$\underline{P_{max} = 13\,580 \text{ lb}} \quad \left(\text{MAXIMUM BIRDSTRIKE LOAD}\right)$$

BEARING LOAD ANALYSIS – UPPER LONGERON FOR ULTIMATE FAILURE

NOTE: UPPER LONGERON IS MADE OF 7075-T7351. ALL OF THE HOLES TO ATTACH THE ARCH HAVE BEEN COLD WORKED PER PS191800.

$F_{bru} = 106$ ksi ($e/D = 1.5$) $F_{bru} = 137$ ksi ($e/D = 2.0$)

$F_{bry} = 86$ ksi ($e/D = 1.5$) $F_{bry} = 104$ ksi ($e/D = 2.0$)

I. FOR SMALLER BOLT AT "A" AND "C"

F_b = BEARING LOAD

t = THICKNESS = .325

d = DIAMETER = $.257 \begin{smallmatrix} +.006 \\ -.000 \end{smallmatrix}$

$\frac{t}{d} = \frac{e}{D} = 1.27$

BEARING STRESS: $\sigma_b = \frac{F_b}{td}$

$F_b = \sigma_b t d$

$F_b = (91700)(.325)(.257)$

$F_b = 7659$ lb

BY INTERPOLATION: $F_{bru} = 91.7$ ksi for $\frac{e}{D} = 1.27$

II. FOR BOLT AT "B" AND "D"

BEARING STRESS: $\sigma_b = \frac{F_b}{td}$

$t = .435$

$d = .312 \begin{smallmatrix} +.007 \\ -.000 \end{smallmatrix}$

$\frac{t}{d} = \frac{e}{d} = \frac{.435}{.312} = 1.39$

$F_b = \sigma_b t d$

$F_b = (99200)(.435)(.312)$

$F_b = 13463$ lb

BY INTERPOLATION: $F_{bru} = 99.2$ ksi for $\frac{e}{D} = 1.39$

THEREFORE, CALCULATING MAXIMUM "P" TO FAIL IN BEARING LOADING

– SINCE THE BOLTS AT "A" AND "C" FAIL AT A SMALLER BEARING LOAD, WE WILL USE THIS VALUE TO CALCULATE THE MAXIMUM BIRDSTRIKE LOAD "P_{max}".

$F_{b_{max}} = 2(F_{b_A}) = (2)(7659)$

$= 15318$ lb

NOTE: MULTIPLY BY 2 SINCE THERE ARE 2 BOLTS.

(MAXIMUM BIRDSTRIKE LOAD FOR BEARING FAILURE)

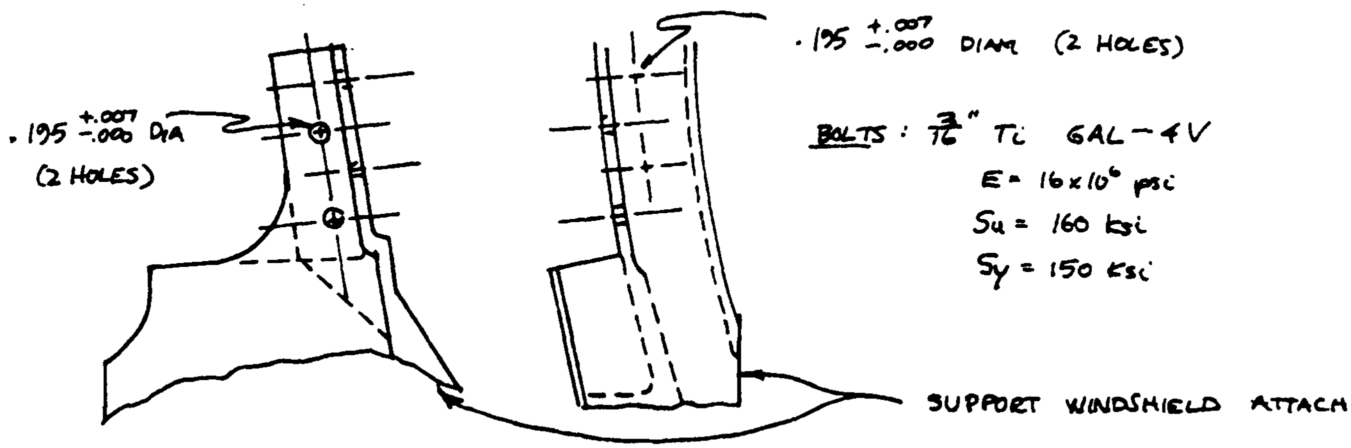
$P_{max} = F_{b_{max}} / \sin 13°$

$= 15318 / \sin 13°$

$\underline{P_{max} = 68094 \text{ lb}}$

$\omega = 68094/3.99 = 17066$ lb/in

FASTENERS THAT CONNECT ARCH



BOLTS: $\frac{3}{16}$" Ti 6AL-4V

$E = 16 \times 10^6$ psi

$S_u = 160$ ksi

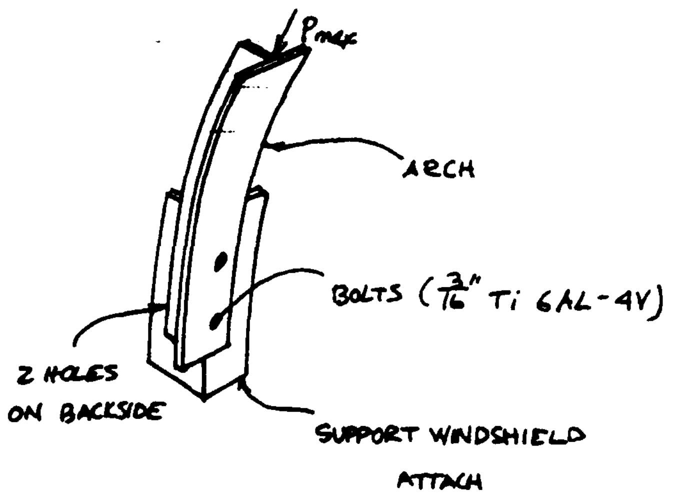
$S_y = 150$ ksi

NOTE: FROM SECTION 4.3.2 THE SAME TYPE OF BOLT IS USED TO CONNECT COLUMN Y240.200 TO UPPER LONGERON EXCEPT THAT IT IS $\frac{5}{32}$" IN DIAMETER. THE MAXIMUM ALLOWABLE SHEAR FORCE FOR THIS BOLT WAS 4000 lb. THIS VALUE WILL BE USED TO FIND THE MAXIMUM ALLOWABLE SHEAR FORCE FOR THE $\frac{3}{16}$" BOLT ABOVE.

$$\frac{4000}{F_s} = \frac{(\frac{\pi}{4})(\frac{5}{32})^2}{(\frac{\pi}{4})(\frac{3}{16})^2}$$

$$F_s = 5760 \text{ lb}$$

THERE ARE FOUR BOLTS THAT ATTACH THE ARCH TO THE SUPPORT WINDSHIELD ATTACH



$$P_{max} = (4)(F_s)$$
$$= (4)(5760) = \underline{23\,040 \text{ lb}}$$

(MAXIMUM BIRDSTRIKE)

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